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AMERICAN INSTITUTE OF MINING AND METALLURGICAL ENGINEERS

(INCORPORATED)

and Petroleum

PETROLEUM DEVELOPMENT AND TECHNOLOGY 1928-29

PETROLEUM DIVISION

PAPERS PRESENTED BEFORE THE DIVISION, AT TULSA, OKLA., OCT. 18-19, 1928, AND NEW YORK, FEB. 20-21, 1929

COMMENCING WITH THIS VOLUME PETROLEUM DEVELOPMENT AND TECHNOLOGY WILL BE DESIGNATED BY THE YEAR IN WHICH IT IS PUBLISHED. FOR CONVENIENCE THIS VOLUME BEARS THE DATE 1928-29

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LETTER OF TRANSMITTAL

H. Foster Bain, Secretary,
American Institute of Mining and Metallurgical Engineers,
29 West 39th Street,
New York, N. Y.

Dear Sir:

I take pleasure in transmitting herewith Petroleum Development and Technology, 1928–29, consisting of 51 papers and discussion on subjects relating to Production Engineering, Petroleum Research, Petroleum Production—Foreign and Domestic, Petroleum Economics, and Petroleum Engineering Education, and including one paper on Petroleum Refining and one on Natural Gas Transportation. It is regretted that the limited space in the volume made it necessary in many cases to limit the discussion. The papers were presented at the Mid-year Meeting at Tulsa, Okla., on Oct. 18 and 19, 1928, and at the Annual Meeting in New York City, Feb. 20 and 21, 1929.

The Tulsa meeting was held immediately preceding the International Petroleum Exposition and it allowed engineers attending our session also to take advantage of attendance at the Exposition. Some 250 engineers attended the meeting and the papers and discussions were of exceptional quality. The papers presented at the New York meeting were well received and a worthwhile contribution to the petroleum industry.

I would like to express my personal appreciation to those who have worked diligently in making 1928 a successful year for the Petroleum Division, and also to thank those who prepared papers and discussions for the two sessions. Organizations interested in technical phases of petroleum development and production have cooperated heartily in preparing programs that would not overlap and to those organizations we are indebted.

I wish also to express my appreciation for the effort of the retiring President, Dr. George Otis Smith, and of yourself and the editorial staff of the Institute in furthering the work of the Petroleum Division during the year.

With the competent officers elected for 1929, it is probable that the scope and activities of this Division will broaden and continue to render value to the petroleum industry during the coming year.

Respectfully submitted,

A. W. Ambrose,

Chairman, Petroleum Division for 1928.

PLANS OF PETROLEUM DIVISION FOR 1929

H. Foster Bain, Secretary,
American Institute of Mining and Metallurgical Engineers,
29 West 39th Street,
New York, N. Y.

Dear Sir:

The plans for the Petroleum Division of the American Institute of Mining and Metallurgical Engineers provide for three principal meetings during 1929–30. The first will be held early in October in Los Angeles, the second, just prior to or following the International Petroleum Exposition in Tulsa, probably late in October, and the third will be the usual annual meeting in New York City in February.

In the preparation of programs for these meetings the committee has had particularly in mind, first, subjects of live interest to the industry, and second, subjects not already handled by other organizations. Among such subjects that group which has to do with unit operations seems to be of greatest importance as the petroleum engineer is not in position at present to outline a fixed program for the development of a unit pool. At the Tulsa meeting, therefore, we will concentrate on well spacing, the time element in a development program and methods of production control, to the end that the greatest amount of oil may be recovered from the sand at the lowest cost.

The California meeting will extend over two days, one day to be given over to technical discussions probably of proration and overproduction from an engineer's standpoint, this being the chief topic of interest in California at present. Field trips will be organized for the second day so that visiting engineers may study the more important methods and types of installation used in California practice.

In addition to the more or less technical studies outlined, one session at the Tulsa meeting will be devoted to hydraulics of flowing wells and another to new developments in miscellaneous phases of the engineer's work.

The February meeting will be organized on a three-day instead of a two-day basis in order to avoid duplication of sessions. Two sessions will be given over to the usual production summary, one to economics, one to production engineering, one to the research round table, and one to engineering education. In addition there will be an evening session which

will include production engineering, production, economics and refinery summaries.

It is expected that the research committee will be particularly active during this year and will work in close cooperation with a similar committee of the American Petroleum Institute and with representatives of the U. S. Bureau of Mines.

In arranging programs special effort will be made to provide for publication in advance of meetings. From the standpoint of the authors, this has the advantage of affording better editing, well considered discussions, good copy for the trade journals at the time of the meeting and separates available at small cost for the author's personal use. It is believed that if the authors of papers fully realize these advantages they will cooperate with the committee to the fullest extent.

In preparing the several programs an effort will be made to systematize the grouping of papers so that they will readily fall into particular chapters in the annual publication. As we will have three instead of two meetings this year it is possible that not all papers submitted can be included in the final volume. However, an effort will be made to print such papers in the Technical Publication series and at least include specific references if not short summaries in the annual volume. It is believed that such papers should be covered by the index which appears in that volume.

Respectfully submitted,
J. B. Umpleby,
Chairman, Petroleum Division for 1929.

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Chapter I. Production Engineering

Rotary Drilling Problems

By R. S. Cartwright,* Ponca City, Okla.

(Tulsa Meeting, October, 1928)

Rotary Drilling Controls

Two types of automatic drilling controls, the Halliburton and the Hild, are now available and are coming into more or less general use in deep drilling. The primary function of both is to maintain a safe limit of torque on the drill pipe, this being accomplished by automatically controlling the weight or pressure on the cutting tool. Neither type will necessarily increase drilling speed, but by permitting advantage to be taken of "breaks" in the hole higher average cutting speed may be maintained. The control is essentially a safety device, and should be considered as such.

It is not the purpose of this paper to discuss the merits of drilling controls, although the advantages over manual feed at the brake drum are obvious, but rather to point out some of the limitations.

The Halliburton Control

The Halliburton control is designed to operate during drilling through the agency of the draw works. Automatic and constant control of the torque on the bit is governed by clutches on the control itself, and the line shaft to drum shaft drives on the draw works. In operations other than drilling the control is simply a jackshaft between prime mover and draw works. It is, of course, adaptable to any type of power.

Because control of the torque on the bit is dependent on the various ratios or clutch combinations available on the Halliburton control and the draw works, it follows that there are certain limitations in points of control. Table 1 shows the possible ratios which can be obtained with the control and a popular type of three-speed draw works, it being assumed that the highest possible gear combination—the combination which when engaged will suspend the least amount of weight—has a value of 1.00.

According to the table there are "blind spots" in the series. This is true particularly among the lowest ratios, which are most used to suspend the major part of the weight when great depths are reached. It will be noted that there is a difference of nearly three units in the value of the

* L. W. Prunty Drilling Co.

Table 1.—*Ratios Obtainable with Halliburton Control and Three-speed Draw Works*

Halliburton Control Speed	Draw Works Speed	Ratio
High	High	1.00
High	Second	1.88
High	Low	3.09
Low	High	2.48
Low	Second	4.64
Low	Low	7.58

two lowest ratios. Low on the control and second on the draw works, with a value of 4.64, will ordinarily be used with 6-in. drill pipe when drilling between 3500 and 4000 ft. When the latter depth is reached this ratio will no longer suspend sufficient weight and it is necessary to employ low on the control and low on the draw works. This will, however, suspend approximately one and two-thirds as much weight as the 4.64 ratio, which, under ordinary circumstances, may not permit sufficient pressure to bear on the bit. The same condition occurs with the other ratios, but not to so pronounced a degree. The significant point is that at extreme depths, where accurate and sensitive control is most desirable, it is least available.

This condition has made it necessary, in order to obtain proper pressure on the bit, to use the brake drum on the draw works as an auxiliary to the control at depths where the "blind spots" occur. To obtain the full value of the control as a governing unit by this practice is not desirable, as it constitutes a partial reversion to the old type of manual feed, with its disadvantages. When the brake must be employed to aid the control in suspending a part of the weight of the drill pipe, it also acts as a brake against the action of the control in hoisting the drill pipe, providing the torque required to turn the bit builds up to a point greater than the power required to lift the pipe and free it for rotation. The net result is that a portion of the effectiveness of the control is destroyed, due to the existing limitations in its gearing to the draw works.

The remedy for this condition appears to be an increase in the number of speeds, or line shaft to drum shaft drives, on the draw works. Four-speed draw works are now available, but the general tendency in new design is to increase the high speed ratios rather than to provide more low speed modifications, which are now the most needed for use with the Halliburton control. Necessary limitations in the size of the draw works will probably not permit of the addition of more than one speed to existing types, and it is suggested that a double line shaft design may be found desirable.

The Hild Drive

The Hild differential drive is designed only for electric power, and hence its operation is confined to those fields where electric power is available. In the Mid-Continent fields, this limits its use to a relatively small part of the total oil-producing area. Another objection is the fact that gear-driven slush pumps for electric drive are required for operation with the Hild unit and have not been available in sufficiently large sizes to satisfy the requirements for deep drilling. They are, however, now being built.

In one important respect the Hild drive possesses a decided advantage over the Halliburton control, namely, that a large number of points of weight control are available, making it more accurate in maintaining a constant torque on the drill pipe, without the necessity of auxiliary manual feed. No change in existing draw works design, unless it would be for the purpose of accelerating pulling out of the hole, is required for its operation.

Elimination of Drilling Controls Not Justified

It has been suggested that weight indicators can take the place of drilling controls, and, in fact, will eliminate them from use. The idea is that the driller, by using a weight indicator, can, with manual feed, maintain a fairly constant pressure on the bit and a constant torque on the drill pipe, thus performing the functions of the control. The writer cannot subscribe to this theory and sees no justification for the elimination of drilling controls. It is true that by closely watching a weight indicator a practically constant pressure can be held on the cutting tool, but it does not necessarily follow that a constant torque, within the safe limits of torsional strength, will be maintained on the drill pipe. In different or mations there is a considerable difference in the torque required to turn the bit, even assuming exactly the same amount of weight is on it, and it is quite within the bounds of possibility that cavings from the hole, particularly a boulder or some such mass, might seriously impede the rotation of the bit, without the addition of a pound of pressure. In such an event, with the control, once the safe limit of power applied to the rotary machine is reached, the drill pipe will be automatically hoisted until the bit is freed, whereas with the manual control upon which the driller must depend when using only a weight indicator, it would be entirely possible to build up sufficient power to twist off the drill pipe. Furthermore, the control, through its automatic action helps to eliminate the human element in drilling, whereas with only a weight indicator the operator must depend upon a driller and his judgment, which may not at all times be infallible. As was previously stated, the drilling control is a safety device which the weight indicator in no wise replaces.

Mud-laden Fluid

The primary purposes of mud-laden fluid, or mud as it is commonly termed, in its application to rotary drilling, are, first, to carry the cuttings from the hole, permitting them to settle out in the circulating pits, and, second, to wall up the hole, once it is drilled, and seal off minor oil, gas or water sands. It serves a further incidental purpose in acting as a cooling medium on the cutting tool, and to a limited extent as a lubricant in the hole. To accomplish these ends effectively it must be of approximately the correct density and viscosity, and must have the property of penetrating sands encountered. It must also permit of easy circulation by the slush pumps.

The average rotary operator does not give much serious consideration to the condition of his mud. Generally it is either good or bad according to the individual driller's opinion and experience. Differences of as much as 3 lb. per gal. in mud in use on wells drilling in the same field, under practically identical conditions, have been observed. On one well a difference of as much as 1½ lb. per gal. during a single period of 12 hr. has been checked. It is not illogical to assume that certain standards could be worked out for the usual drilling conditions, and that greater drilling efficiency would result if the correct type of mud were maintained, rather than depending on the hit-or-miss methods sometimes followed.

Mud is a colloidal suspension of finely divided clay in water, the clay being derived from the formations encountered in the hole and the mixture resulting from the cutting and churning action of the cutting tool with water flowing at high velocity from the slush pumps. When drilling in a clay-bearing formation there is a tendency to "make" mud—to form a heavier colloid—while in other formations, particularly sand, there is the opposite tendency, that is, for the mud to thin. Normally, there is an excess of mud-forming material drilled, such excess clay settling out in the circulating system, and making it possible, by mixing or thinning with water, to maintain a fluid of fairly identical characteristics.

Test for Mud

As a quick and effective method of testing various samples of mud the writer employs an ordinary centrifugal oil-testing machine. When rotated at a high velocity for a known time the samples separate into their constituent materials, and by using graduated tubes it is readily possible to determine the exact amounts of cuttings, free water, etc., in each. Table 2 shows the results of such a test on four typical muds, taken from four different deep wells in the Mid-Continent district.

The several samples differ greatly, although the four wells from which they were taken were drilling under about the same conditions, and the muds were considered suitable by each operator.

TABLE 2.—*Analyses of Four Typical Muds Used in Mid-Continent Wells*

Sample No.	Free Water, Per Cent.	Clay Residue, Per Cent.	Cuttings, Per Cent.	Weight per Gallon, Lb.
1	2.1	20.7	0.3	9.90
2	1.4	23.0	14.0	9.75
3		26.8	17.8	10.60
4	0.9	20.6	14.2	9.90

It is obvious that the amount of free water should be maintained at a minimum, and that an excess indicates an unstable colloid. The clay residue is largely dependent on the weight of the mud per gallon and varies with it, but should, if the proper weight is maintained, be kept at the lowest possible point. With it, as with free water, the amount deposited is in direct ratio to the stability of the colloid. Cuttings, by which is meant foreign nonmud-forming constituents such as sand and shale, should also be limited as much as possible. Not only do they cause excessive wear in the slush pumps, but in the event of failure in the circulating system they are liable to settle around the bit, preventing either rotation or hoisting.

The most practical test for everyday purposes is a careful check of the weight per gallon. If the operator will do this, he will find it easy to maintain whatever standard his experiments prove most desirable. For all general purposes the writer has found that a mud weighing about 10 lb. per gal. is best. In such a mud the free water should not exceed 2 per cent., the clay residue 19 per cent., and the cuttings 1 per cent.

Effect of Heavy Mud

A mud which is too heavy builds up on the walls of the hole and hinders getting back onto bottom after having pulled out. The depositing action on the walls is particularly noticeable in sand formations, and while it is desirable that a sand should be sealed off, mud much heavier than 10 lb. per gal. has a tendency to so reduce the diameter of the hole that it is difficult to get a full gage cutting tool through, thus delaying drilling operations and often requiring some time for reaming the hole back to full gage. If the colloid is especially stable, it is, of course, possible to use a heavier mud without much settling, but such is not usually the case, and it has been the writer's observation that where mud as heavy as 11 lb. per gal. has been regularly used, considerable time has been required to get back on bottom after a trip out of the hole.

Mud much below the standard of weight favored by the writer, is not sufficiently heavy to carry the cuttings from the hole, thus impeding the progress of drilling. Nor will it properly wall up the hole, making it liable to caving, with consequent loss of drilling speed and danger of sticking.

Removal of Cuttings

The most effective method which I have found for settling out cuttings is the use of a long ditch or conductor, through which the mud must pass as it is discharged from the hole. It has also been found that passing it through a settling pit, where it is forced to spread out over a wide area, is also effective for this purpose and leaves the circulating pits free of foreign matter. If the weight of the mud will not be too seriously reduced it is also advisable to inject a small stream of water into it as it is discharged from the hole, in order to facilitate removal of the cuttings.

There is a general opinion among some drillers that the deeper a well is drilled the heavier the mud should be. This theory cannot be sound, for mud performs the same functions at 5000 ft. that it does at 2000 ft., and any increase in weight will result in the conditions already referred to. This is assuming, of course, that heavy gas pressures will not be encountered. If such is the case the mud must be as heavy as is practical to handle, or rather, sufficient to maintain hydrostatic pressure at the bottom of the hole to more than equal the sand pressure.

It is common practice with some operators, after reaching considerable depths to use some crude or fuel oil in the mud, their purpose being to provide a lubricant and a solvent for shale cuttings which might settle around the cutting tool if circulation were suspended. The writer has found that the addition of oil for this purpose is not desirable, as its actual effect is to coat the finely divided cuttings, as in the flotation method of ore separation, making it almost impossible to get them to settle out. There is the further objection that a mud mixed with oil is difficult to handle in the slush pumps, as it has a solvent action on the balata valve disks commonly used in mud pumps. He suggests that the concentration of oil be not permitted to reach more than 2 per cent. by volume.

If the cutting tool is stuck, and can neither be hoisted nor rotated due to cuttings settled around it, it is often possible to free it by circulating oil. On the few occasions that it has been possible for the writer to check the concentration of oil required for this purpose, it has been found that not more than 25 per cent. by volume is necessary, although in extreme cases pure oil and not an emulsion with mud is required.

Use of Clay Substitutes

When there is no reserve supply it is necessary to use some substitute for clay in mixing mud. Ordinarily, cement, lime or plaster, which are easily procured, is used. They are not very satisfactory because, in spite of thorough mixing, they rapidly settle out. Barium sulfate and iron oxide form true colloids, and either, if available, is much to be preferred as a mud-making substitute. For adding weight to mud, iron

oxide is particularly desirable as it can be readily used to make a mud weighing from 15 to 16 lb. per gal. When the addition of such material is necessary, it is common practice simply to dump it in the circulating pits. By using a small tank conveniently located on the derrick floor, and connecting it directly to the slush pump suction pipe one can obtain exactly the mixture desired without sustaining any loss in getting it into circulation.

Mud for Deep Drilling

Due to the limitations of existing equipment, it has not been possible to make extensive experiments with reference to the proper volume of mud for deep drilling. The writer has found, however, that a volume of from 400 to 450 gal. per min. with a pressure of about 500 lb. per sq. in. is desirable for a hole of 11 or 12 in. dia. For maximum drilling speed the bit must be kept clean by washing, and all cuttings washed from the hole ahead of it. In hard formations, where drilling speed is reduced, it is entirely possible and desirable in order to save fuel to reduce the volume, but it may be generally concluded that up to a volume of 450 gal. per min., cutting speed per unit of time is in direct ratio to fluid volume. For holes smaller than 11 or 12 in. dia. it is probable that the volume should be calculated on the basis of the area of the hole for maximum efficiency. It is considered entirely possible, in a small diameter hole, to "wash" the hole, that is, to circulate a sufficient quantity of fluid under high pressure, particularly in soft formations, to cause side wall caving, and it is suggested that this point must be kept in mind in all volume calculations.

A check of the fluid efficiency of slush pumps might prove interesting to many operators. Only by exercising considerable care has it been possible to maintain an efficiency of 70 per cent., which is probably considerably higher than the general field average. If the recommended volume of at least 400 gal. per min. is to be maintained most of the slush pumps now in use must operate at not less than 65 per cent. efficiency. It will undoubtedly be found that efforts toward that end will be amply repaid in increased cutting speed.

In this connection, it may be mentioned that the development of large power-driven slush pumps is highly desirable. A number of manufacturers are now working on this problem, but it is certain that if other forms of power than steam are to be applied to rotary operation larger and heavier pumps for power drive than have hitherto been available must be supplied to meet the competition of steam equipment.

Distribution of Time in Rotary Drilling

It is obvious that the time factor is of primary importance in rotary as well as other methods of drilling. Tools can be made to pay a reason-

able profit only by making reasonably good time in completing a well. From the standpoint of fuel and water consumption increased drilling speed also means decreased drilling costs. Moreover, in a highly productive area where flush production is important, a higher rate of drilling speed means much quicker and greater returns. It is well known that at times bonuses of considerable magnitude have been paid in an effort to stimulate drilling operations.

A study of the distribution of time spent on rotary drilling wells was therefore undertaken, with the idea of increasing general efficiency by increasing the amount of effective drilling time and decreasing the amount of lost or ineffective time. No two wells ever drill exactly alike, and, due to the great differences in other factors governing speed of drilling, it does not necessarily follow that one with an average of 75 per cent. effective time will make more footage than another with an average of 60 per cent. effective time. It is believed, however, that the effective time to the total time ratio will serve as a fairly accurate index to drilling speed. There can be no argument on the point that hole can be drilled only by "setting it on bottom and turning it to the right."

A Study of Four Oklahoma Wells

The figures which follow are based on a study of four deep wells, drilled within the past year, in north central Oklahoma, the first being an 11-in. hole drilled to 4455 ft., the second an 11¾-in. hole drilled to 4100 ft., the third a 12-in. hole drilled to 4200 ft., and the last an 11-in. hole drilled to 4100 ft. Three of these wells were drilled in the fall and winter of 1927, when weather conditions were not entirely favorable. Two were drilled in the immediate vicinity of producing wells, while two should be considered as wildcats. All were Wilcox sand wells, with an eventual depth in excess of 5000 ft. The equipment was of late design, and may be considered as representative of the best rotary machinery now available. All were powered with steam. As a whole, the four wells probably represent a fair cross-section of the most difficult drilling conditions now encountered in the Mid-Continent fields.

It should be noted that time spent in rigging up preparatory to starting a well, and time lost while waiting for cement to set around casing is not taken into consideration. No allowance is made, either, for time lost in fishing or establishing lost circulation, nor for shutdowns arising from fuel or water shortage. The time covered is only such as would normally be required for rotary operation, all conditions being favorable.

Fig. 1 shows the average effective drilling time for the four wells. The curve as a whole shows a steady decline from approximately 80 per cent. to approximately 57 per cent. From the surface to 2000 ft., drilling time averaged 81 per cent. of the total elapsed time, with lost time amount-

ing to 19 per cent. Between 2000 and 3000 ft. drilling time fell off to about 76 per cent., and lost time rose to 24 per cent. From 3000 to 4000 ft. drilling time declined to 70.5 per cent., and lost time increased to 29.5 per cent., while between 4000 and 4500 ft. drilling time dropped to 57.2 per cent., and lost time rose to 42.8 per cent.

For the purpose of comparison, Fig. 1 contains a line showing the highest average of effective time maintained on any one of the four wells

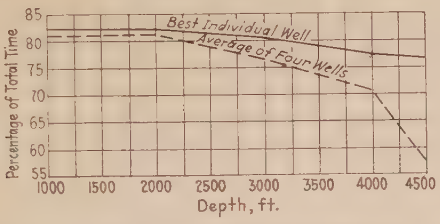

FIG. 1.—EFFECTIVE DRILLING TIME AT VARIOUS DEPTHS ON FOUR ROTARY WELLS.

considered. It will be noted that at every point in the hole, the curve shows a decided betterment over the general average, amounting at the extreme depth of 4500 ft., practically to a 20 per cent. difference, which indicates that it is quite possible to improve on the record of what may be termed good rotary practice.

A reduction in drilling time due to increasing depths is to be expected. The significant fact, however, appears to be that from 4000 ft. down the decline becomes abrupt. This presents a serious problem to the operator, inasmuch as a considerable proportion of the wells now being drilled in the Mid-Continent fields have eventual depths in excess of 4000 feet.

Increasing Effective Time

The only method of increasing effective time is to decrease lost time. This was analyzed with reference to the various operations incidental to

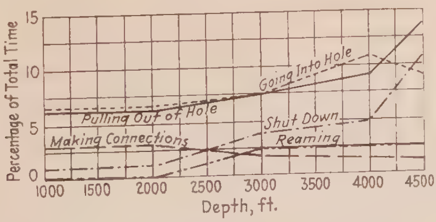

FIG. 2.—LOST TIME ROTARY DRILLING.

rotary drilling (Fig. 2). Time for going into the hole is that required to lower the bit and pipe into the hole preparatory to drilling. Time for pulling out of the hole is that required for withdrawing the bit and pipe

from the hole, either for the purpose of putting on a fresh bit or for making any repairs or changes that necessitate the suspension of drilling. Time for making connections is that required for adding pipe to the string in the hole, in order to continue drilling. Time for reaming is that required to bring the hole already drilled out to the full gage of a fresh bit, or to get on bottom due to the presence of cavings in the hole. All other lost time, such as that required for making mechanical adjustments, repairs, etc., is included in shutdown time.

Fig. 2 shows, in general, a steady increase in the time required for the various operations. The time for going into the hole increases steadily between the surface and 4000 ft., but from that point down it decreases, probably because at extreme depths fewer bit changes per unit of time are normally made than at shallower depths, a rock bit being used exclusively with no short runs of a disk or fishtail bit. The time for pulling out of the hole increases steadily, following closely the time for going into the hole up to 4000 ft., at which point it has a sharp increase that more than compensates for the decrease in the time for going in. This is probably due to the greatly increased weight of the string of drill pipe below 4000 ft. requiring more careful and slower handling, especially if additional lines are strung in the traveling block.

The time for making connections shows a steady decline from the top of the hole to the bottom, being an exception in this respect. This is to be expected, however, for normally the deeper a well is drilled the less footage per unit of time is made, and hence the fewer additions of pipe are required. Time for reaming shows a slight increase up to 3000 ft., but from there on down is constant. It is subject to the condition of the cutting tool, the formation drilled, and the condition of the hole. The time for shutdown has a normal rise to 4000 ft. From that point down it has an abrupt rise, the increase in percentage of total time being greater than for any of the other operations considered.

Shutdown Time an Important Item

It is not the purpose of this paper to go into ways and means of increasing effective time, but it is suggested that Fig. 2 shows quite clearly that the item of shutdown time is the one which should first receive consideration. The very considerable increase in this item for wells below 4000 ft. also indicates that if wells are to be drilled successfully at constantly increasing depths, shutdown time must be held to a minimum.

Because of the lack of data it is impossible to make a comprehensive comparison between California practice and the figures presented in this paper. One well drilled on the West Coast to an approximate depth of

3800 ft. showed an average drilling time of only 37 per cent., but one well cannot, of course, be assumed as a criterion of California practice.

Daily time records of all drilling wells may be kept. With such a record it is readily possible for the individual operator to know how every hour of the twenty-four is spent, and to work out his own standards.

Relation of Weight on Rock Bit to Cutting Speed

There are three factors which limit the permissible weight on the rock bits during the course of drilling formations usually encountered in the Mid-Continent fields. First, there is the fact that the rock bit cone bushings or bearings will not, under rotation, at depths below 2000 ft., support more than a part of the total weight of the string of drill pipe without excessive wear or crushing and consequent ruin of the cones or cutters. It is of course possible to operate the rock bit in two distinct ways, as is true of any cutting tool. The weight may be held off the bit and a high speed of rotation maintained, or more weight may be set on the bit and the speed of rotation decreased. Both methods have advocates, but experience has shown that generally more footage, at about the same cutting speed, can be secured by following the latter course. This method is to give the bit a considerable amount of weight and rotate it at a speed not to exceed 40 r.p.m. for 11-in. and larger size holes and 30 r.p.m. for 8-in. and smaller sizes. It is often possible to increase the rate of cutting speed by giving the bit a considerable amount of weight, and rotating it up to 60 or 70 r.p.m. This, however, usually results in excessive cone bushing wear and requires more trips out of and back into the hole, to put on fresh bits. Additional time so spent is lost and, when cutting speed is balanced against total time, the resultant average footage per hour is no higher than it would have been had the speed of rotation been low.

Torsional Strength of Drill Pipe

A second factor which must influence the amount of weight used in drilling is the drill pipe itself. It is obvious that the torsional stress to which the pipe is subjected must increase with the amount of weight on the bit. It is true, also, that the rate of increase is by no means as high with a rock bit as with a drag bit of the fishtail type. The writer does not know of any work that has been done along this particular line, and it would be almost impossible to formulate theories for general application, since no two holes are identical and there is a wide range of difference in side-wall frictional resistance. However, I have observed that when the amount of weight on the bit goes over a maximum of approximately 41,000 lb., there is a tendency for 6-in. drill pipe to bend and kink, par-

ticularly at the bottom or rock-bit joint, which would indicate that the limit of safe operation with reference to the torsional strength of the drill pipe was being approached.

Angle of the Hole

The third factor limiting the amount of weight on the rock bit is the maintenance of a uniformly straight or plumb hole. It is obvious that as more weight is put on the cutting tool, the greater the tendency is for it to slide with or follow along any formation which is inclined from the horizontal with reference to the surface. As a general rule the slope of formation is not sufficiently abrupt in the Mid-Continent fields to affect greatly the angle of the hole, but there are exceptions to this which have resulted in serious losses. Considerable trouble has recently been encountered, on this account, in the deep wells drilling in the vicinity of Marshall, Okla., the difficulty apparently centering in a formation at 900 ft. When such a condition does exist too much weight on the bit will become a serious factor in aggravating the tendency of the bit to go off center.

Recommended Weights on Bits

Manufacturers of rock bits make certain recommendations as to the amount of weight which it is advisable to carry on their bits. In an 11-in. hole with 6-in. drill pipe the Hughes Tool Co. advises 11,000 lb. for medium sand, 14,300 lb. for hard lime and 17,600 lb. for granite or basalt. For identical conditions the Reed Roller Bit Co. recommends 7000 lb. for sticky shale, 10,000 lb. for sand, 13,300 lb. for hard lime and 16,500 lb. for granite or basalt. It has been the writer's observation, however, that these weights are greatly exceeded in actual practice, and, in fact, the recommended weight represents only a fractional part of the weight required to secure anything approaching a good average cutting speed.

TABLE 3.—*Cutting Speed of Bit for Different Weights on Bit*

Weight on Bit, Lb.	Formation				
	Lime, Ft. per Hr.	Sand, Ft. per Hr.	Sandy Lime, Ft. per Hr.	Shale, Ft. per Hr.	Sticky Shale, Ft. per Hr.
23,000	1.9			2.94	2.47
26,000	2.5	4.0		2.95	3.23
29,000	3.4	3.04		2.97	2.80
32,000	3.78	5.24		3.72	2.38
35,000	3.9	4.76	3.03	4.19	3.7
38,000	3.0	4.14	3.85	4.13	4.44
41,000	4.1	4.05	4.99	3.94	3.5

In an effort to determine the advisable weight for drilling an 11-in. hole with 6-in. drill pipe in the various formations commonly encountered in the Mid-Continent field, the writer has from actual records plotted cutting speed against the weight on the bit. Table 3 shows the results of these calculations, giving the cutting speed of the bit in feet per hour for every variation of weight from 23,000 to 41,000 lb., in the five formations which are ordinarily logged. Fig. 3 gives the same information in graphic form. In considering the figures presented, it should be borne in mind that cutting speed as shown is calculated only for actual drilling time. No effort was made to allow for lost time due to the wide variations to

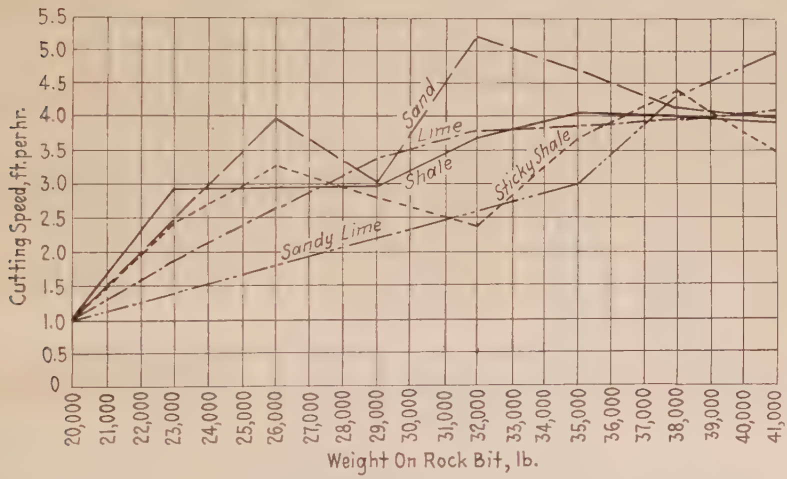

Fig. 3.—Cutting speed rotary drilling with varying weight on rock bit.

which it is subject, and to the fact that these figures are only for formations between approximately 2000 and 4000 ft. Cutting speeds of less than 2000 ft. are considerably higher than the averages shown here, due to the greater degree of softness of the formations drilled, and to the fact that up to that point a very considerable part of the hole may be made with either fishtail or disk bits. There is not yet available sufficient information to make a profitable study of the weight factor at depths below 4000 feet.

Table 3 shows clearly that, as a general rule, there is a steady increase in cutting speed proportional to the increase in weight employed. The average for 23,000 lb. is approximately 2.44 ft. per hr., whereas at 41,000 lb. the average is nearly 4.12 ft. per hr., which would appear to indicate that the latter weight, which is generally found not to be excessive for safe operation, is productive of a considerable increase in drilling speed. In general it might be concluded that between approximately 20,000 and 40,000 lb., rock bit cutting speed per hour under normal conditions is about 1 ft. for every 10,000 lb. weight on the bit.

Further examination of Fig. 3 shows, however, that about 38,000 lb. is the most effective weight. At this figure the highest footage per hour is approached for each of the five formations considered, and beyond that weight the curves tend either to flatten out or to show an actual decline. Because the stress on cone bushings or bearings is less at 38,000 lb. than at 41,000 lb., and because as high a cutting speed can be maintained at the former figure, it would appear that 38,000 lb. offers the best general average.

A study of the individual curves as they appear shows a steady increase in cutting speed for lime, with only a slight rise, however, beyond 32,000 lb. The curve for sand is the least regular of any. It shows a sharp decline between 26,000 and 29,000 lb., and an even more abrupt rise between 29,000 and 32,000 lb. From that point on the decline is relatively constant. The writer is not prepared to offer any explanation of this apparently erratic behavior, but is inclined to believe that it arises from differences in the cementation of various bodies of sand, and the resultant ease with which they chip or break under the impact of the rock bit teeth. The curve for sandy lime shows a normal increase up to 35,000 lb., at which point the rise is accentuated, continuing to 41,000 lb. The shale curve shows a relatively slow rise up to 24,000 lb., rises normally to 35,000 lb., and then flattens out with a slight fall to 41,000 lb., while the curve for sticky shale, behaves somewhat as does the curve for sand, exhibiting a normal rise only between 32,000 and 38,000 lb. It was found that a very low rotational speed with comparatively light mud was most effective for drilling in this particular formation.

The figures given here are not conclusive as a much larger number of wells would have to be taken into consideration before making any definite conclusions, but they do indicate that considerably more weight than is recommended by manufacturers is desirable for rock bit operation, and that there is a definite relation between cutting speed and the amount of weight on the bit.

Correct Weight for Disk Bit Operation

A close check of the weights for disk bit operation has not been made, but casual observation indicates that the correct weight is in the neighborhood of 20,000 lb. There is little or no opportunity in the Mid-Continent field to make a study of fishtail bit operation, but some authorities in California, where this type of cutting tool is widely used, recommend from 6000 to 10,000 pounds.

In recent operations in Colorado, where very hard granite was encountered and which was drilled into approximately 230 ft., about 25,000 lb. was found to be the advisable weight. With more than that amount the teeth were very rapidly cut off the rock bit, and the cone bushings showed

excessive wear due to abrasion from particles of the granite which would work in between the cones and bushings. No formation comparable to this is encountered in the Mid-Continent fields.

Weight Indicators

Devices for weighing the load on the derrick, usually called weight indicators, are coming into general use, for deep drilling in the Mid-Continent fields. Indicators are of two types, namely those measuring the deflection of the derrick as a load is imposed, and those weighing the load directly by attachment to the dead line. The first have not proved very satisfactory. There is no standardization of derrick design, and hence there is no generally applicable formula for determining the amount the various derricks will deflect under different loads. Furthermore, most derricks are subject to misalignment, which will constantly increase with a steadily applied load, and frequent adjustments are necessary on any instrument which measures deflection at a given point. This paper will therefore consider only the dead line type of weight indicator, which is now used almost to the exclusion of the other type.

This type, as the name implies, is attached at any convenient point to the dead or stationary end of the drilling line. The line is held in a kink by the weight indicator, and tends to pull straight under load. In so doing it exerts a pressure proportional to the load against a diaphragm. This pressure is measured by ordinary gages, each unit of pressure representing a predetermined load value. The diaphragm unit is the only part of the assembly having special or patented features, any type of pressure gages being applicable for indicating the load. In practice, an ordinary gage is so placed as to be readily visible to the driller, with a recording gage placed at a protected point.

Weight indicators have certain definite advantages. They measure the total load of the drill pipe when running into or coming out of the hole. During the course of drilling they measure the weight or pressure imposed on the cutting tool, and when a recording gage is used, they provide a permanent record of operations.

Weights Handled

In pulling the drill pipe out of the hole, or in handling long strings of casing it is obvious that there is not only a very considerable amount of weight to handle, but there is also the friction against the sides of the hole to overcome. Weights of approximately 250,000 lb. have been recorded in starting off bottom with the bit caught in a caving hole. It is not inconceivable that, at extreme depths with 6-in. or larger drill pipe, weights

of as much as 300,000 lb. may be reached. Such loads approach the limits of tensile strength of the hoisting equipment now in use. High-grade rotary wire drilling lines of 1-in. dia. have a recommended working stress of from 9 to 10 tons, with a breaking stress of approximately five times that figure. A load of 250,000 lb. distributed on seven lines gives a load per line of about 18 tons, or double the recommended working stress for a new line. If the line should be somewhat worn, excessive loads may cause breakage and consequent dropping of the drill pipe. There is the same possibility of breakage in the elevator, elevator links, and the hook, and even of pulling the pipe apart, while derricks under extreme loads may collapse. It is therefore, highly desirable to know, in the event of a hard pull, approximately what the load is, in order to keep it within the safe working limits of the equipment used. We have found that it is necessary to instruct all drillers regarding the maximum pull allowable.

At depths below 2000 ft. it is not normally desirable to set the entire weight of the drill pipe down on the cutting tool. It is advisable to suspend at least a part of the weight from the draw works brake drum or drilling control. As pointed out elsewhere in this paper, varying amounts of weight or pressure on the bit may be desirable in different formations to get maximum cutting speed. Furthermore, as a well is drilled deeper and more drill pipe is added to the string, the weight of the entire string increases so that there is no constant ratio between the permissible pressure on the bit and the weight of the drill pipe. It is therefore desirable that the amount of weight on the bit be known at all times. The weight indicator satisfies this requirement and permits of accurate regulation, regardless of depth.

Use of Recording Gage

In the absence of other means, a recording gage will, when used with the weight indicator, give the operator a permanent record of his operations. Drilling time, lost time, maximum loads, drilling pressures, and other valuable data, the compilation of which would be of great service to the individual operator, can be readily secured from recording gage charts. It is suggested that through this medium it is now possible to make comprehensive studies of rotary drilling, and to raise the general average efficiency of rotary operation.

The most serious fault of the weight indicators now available is that they are not as accurate as is desirable. They will not register, under ordinary conditions, load changes of less than 2000 lb., which, particularly with a fishing job, is not sufficiently close. Experiments are now being conducted with electrical indicators and it is believed that in the near future instruments of much greater accuracy than are now available will be perfected.

A further minor fault in existing types of weight indicators is the fact that continued hard pulling tends to set the kink in the dead line, upon which the action of the weight indicator depends, making an occasional change in its position necessary. Some trouble is also encountered in maintaining perfectly tight conduits from the diaphragm unit to the gages, but this is purely mechanical and can be corrected by the operator in the field.

It should be borne in mind that the dead line indicator can only be used on the dead line. If it becomes necessary to string the casing or drilling line so that the dead end is tied into the traveling block instead of to the calf wheel or derrick base, there is no point to which the indicator can be attached.

DISCUSSION

I. G. Harmon,* Ponca City, Okla. (written discussion).—There are so few points in Mr. Cartwright's paper which are even open to argument that I will take very little time in discussing the technical features of it. I do wish to emphasize the importance of the Hild differential drive which has been used more on the west coast than in the Mid-Continent fields, because of the more general availability of electricity, and the Halliburton control, which is beginning to be used in the Mid-Continent.

At this time the Marland Production Co. will not let a contract for a deep rotary well unless the contractor guarantees to use the Halliburton control. We feel justified in taking this position for several reasons. We have noticed that our contractors using Halliburton controls seldom have fishing jobs, consequently this results in the well being drilled more cheaply than otherwise. We know by experience that deep rotary wells unless drilled with automatic control are very likely to be crooked, and we know that crooked wells cost us a great deal more to produce than straight ones. In one field, we have wells to the Wilcox sand drilled with the Halliburton control and on the same lease wells drilled without the Halliburton control. The difference in operating expenses is a very considerable item.

We find that some of our contractors who have been drilling with the Halliburton control and are thoroughly sold on it are willing to take difficult deep wells for less money than other contractors who are not experienced with the Halliburton method. These same contractors assure me that they are making a fair profit, and as I see their operations enlarge, I am inclined to think that they are successfully conducting their business.

When I was invited to discuss this paper, I said that I did not care to discuss it from a technical point of view: first, because I believe that the facts set out in the paper are so fundamentally sound that they are not open to discussion; second, for the reason that I believe that there is another angle of our drilling problem which should be presented to this society in a manner to emphasize its importance.

In discussing the production of oil with old-time producers, many of whom head our large oil companies, we constantly hear the question, "Why do we not drill oil wells as cheaply now as we did in the past?" The reasons why we cannot do so are somewhat evident, it appears to me. We know that we do not have as efficient labor as we once had and unfortunately few of the better type of oil-field workers are willing to learn the drilling business. The wage scale, in keeping with the general trend of the times, has increased several fold. In addition to this, we are drilling deeper

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* Marland Oil Co.

holes, running heavier and better pipe, heavier and better drilling equipment of all kinds, and consequently we are spending much more money for material and equipment than we did in the past. Our deep holes make this necessary.

The problem confronting us is, "How can we drill oil wells for less money?" I have just compiled, from the records of the Marland Production Co., certain information for the purpose of emphasizing the importance of this problem. During 4 years and 8 months, ending the thirty-first day of August this year, the Marland Production Co. drilled 942 net interest oil wells. These wells were scattered throughout Oklahoma, Kansas, Colorado, Texas, Louisiana and Arkansas. They represent all kinds of drilling conditions and depths, varying from shallow wells to deep wells. The total expenditure for all these wells was $32,870,000, of which $14,662,000 was for material and $18,208,000 was labor and other intangible drilling costs. During this same period of time Marland Production Co. produced 31,000,000 bbl. of oil, with a total net lifting cost of $9,437,000, which includes all taxes and overhead. In other words, we spent almost four times as much money for drilling oil wells as we did for producing the oil. We spent twice as much for intangible drilling costs alone as we did for producing the oil. During the past 2 years and 8 months, the Marland Production Co. has written off against its production all of its intangible drilling costs. This has resulted in a write-off of 99 c. bbl. During this same period of time, the lifting cost, including tax and overhead, has been 31 c. per bbl. In other words, from any standpoint that one figures it, we are putting three times as much money into the drilling of oil wells as we are into the lifting of oil. Notwithstanding this fact, our engineers have concentrated on our lifting-cost problems, on our gas-lift, and repressuring problems, on our material and equipment tests and on other production problems. I know of few companies whose engineering staff is devoting much time to a serious study of drilling problems.

According to these figures, if we could reduce the total cost of drilling an oil well 25 per cent., we would reduce the cost of producing a barrel of oil in the neighborhood of 30 to 40 c. Is there any more worthy or important problem to which the engineers of the oil industry and of this society can devote their energies?

It appears to me that there are a number of very apparent ways of attacking our drilling problem. First is that of power equipment. Most of our oil wells are drilled today with steam or gasoline engines and it is my belief that there is no less efficient piece of equipment in the world than an oil-field boiler as it is commonly set up and used. The water and the fuel bills are exorbitant. In many areas, such as West Texas, a boiler will not last long enough to drill one well. The gas or gasoline engine does the work, but like any other high-speed engine of this type, its life is short and our experience is that a year or a year and a half of service is all that can be expected of it.

It is my belief that in the future, the power for drilling oil wells will be generated by full Diesel engines, probably directly connected to direct-current generators, either as individual units or in central installations on leases. In the past, Diesel engines have been designed with no thought of portability. The more metal that could be added to the engine, the more likely the salesman was to get the contract. This condition is rapidly changing. I believe that direct-current generators directly connected to Diesel engines are the desirable installation, because of the variable speed and because of the perfect drop allowed the tools. Our contractors prefer drilling with electricity to any other method. One of our contractors recently completed a 4230-ft. cable-tool well in southeastern New Mexico, in 51 days. This well was drilled with electricity, generated by a gasoline engine.

A field Diesel engine should very materially reduce the fuel and water bill to a figure much less than it has been with steam. The fuel and water for drilling the

942 wells mentioned cost our company $1,335,000. A 50 per cent. saving would be altogether possible with Diesel engines.

Mr. Cartwright's paper points out the lost time running in and pulling out in rotary holes; the figures given are far better than the average contractor can show. If we were able to devise a method of drilling rotary wells so that hole would be made rapidly in hard rock and so that we would not have to spend an unreasonable amount of time running in and pulling out, we would practically eliminate cable tools. This is a desirable thing to do, (1) because good cable-tool drillers are hard to get, much more so than good rotary drillers; (2) the elimination of cable tools eliminates a great deal of pipe; (3) rotary holes, when once a satisfactory bit is found, will almost always be drilled faster than cable-tool holes. Consequently, all these facts considered, we should be able to drill rotary holes much more cheaply than cable-tool holes. Any bit that will rapidly drill hard rock formations will, in all probability, be dependent to a great degree on speed. The present rotary drilling speeds are not sufficiently high to operate high-speed bits.

Would it be impossible to develop a multiple stage motor to be run into the hole on a string of drill pipe, only the motor and bit to rotate? The bit might be made of carborundum or the new hard metal carbol, which the General Electric Co. has recently developed, and which is reported to be harder than glass, and capable of cutting a thread in glass. I do not believe that such an idea is fantastic, but of course it will take a great deal of study, experimentation and money to perfect such equipment.

I have offered the suggestions with reference to the Diesel engine and the electric generator and multiple-stage motor and the high-speed bit only as suggestions of a few ways of attacking the drilling problem, when in reality there are many ways of attacking it. This problem must be worked out in conjunction with the manufacturer of engines and motors and bits and in consultation with metallurgists and other specialists.

J. R. Suman,* Houston, Tex. (written discussion).—Weight indicators, as mentioned by Mr. Cartwright, are coming into general use. Many of the drillers need more instruction in the reading of both the indicating and recording gages. The indicating gage is quite commonly an ordinary 100-lb. gage, but many drillers think that this gage reads in tons, no matter how many lines are strung up. All crews should be furnished with tables from which they can quickly determine the weight being carried according to the number of lines strung up.

Mr. Cartwright's deductions as to the efficiency of mud pumps are very good. We have checked a number and rarely find one over 60 to 65 per cent. efficient.

The correct consistency of drilling mud is a vital factor to successful holemaking and yet is given little attention. It varies greatly in different districts. In West Texas the operators prefer to drill with clear water, which is used until it becomes necessary to load the hole to prevent blowouts. Tests show that much faster time is made with the clear water and the cone bushings on the rock bits last much longer. Increased carrying capacity for cuttings in this case is achieved by increasing the velocity of the mud stream instead of increasing the specific gravity.

Mr. Cartwright's deductions as to increasing cutting efficiency by speeding up the pumps is sound in almost all formations. It occurs to me, however, that we have about reached the limit in pump size and therefore in mud velocities. I would like to suggest a simple expedient for helping out in this connection. We now have blowout preventers which rotate with the Kelly joint and it is very easy to drill with rotary equipment, keeping the fluid under controlled pressure. By the simple expedient of reversing the line of flow of the mud and making it come up through the drill stem we can triple the velocity of the mud-laden fluid which carries the cuttings and thereby

* Director Production Dept., Humble Oil & Refining Co.

enormously increase the size of material we are excavating. Under this system we can lower the size of the pumps with corresponding mechanical efficiency on the derrick floor and excavate more material than we are now handling. The reverse return system of drilling has been tried on the Gulf Coast with very satisfactory results and I venture to predict that it will come into more and more common use over the United States in the next five years. I would also venture the suggestion that we try to get some more efficient pumping equipment and am wondering why plunger pumps or compound centrifugals will not handle mud more cheaply than the present type of piston pump.

The most vital factor that concerns the efficiency of rotary drilling is the relative percentage of time the bit can be kept rotating on bottom. Rapid strides are being made outside of Oklahoma in increasing this effective drilling time. This is being done with new types of substitutes for fishtail bits and the rapidly gaining use of hard surfacing alloys and chemicals such as tungsten carbide. Fewer round trips with drill bits is the best way to increase this effective drilling time. Of course, in Oklahoma, where the rollers and core type of rock bits are used so extensively, this is hardly possible. In Texas, the old-fashioned fishtail bit is rapidly going out of use. If you use it in Oklahoma at all, I would consider it responsible for your crooked holes.

C. V. Millikan,* Tulsa, Okla.—One well drilled with a fishtail bit made 1100 ft. in 36 hr. drilling time and was not over one degree off vertical. A rock bit was used below 1100 ft. and the hole became more and more off vertical to 3500 ft., where it was off over 20°.

K. C. Heald,† Pittsburgh, Pa.—I would like to ask about the automatic control. Is it not true that with such control you can put more pressure on the bit than without such control, and that unless it is carefully handled you will have just as much trouble as with any other type?

A diagram like that on page 21, without additional statements, leaves readers like myself, who are not in close contact with activities in the field and who must get their information from just such papers as this one, greatly in doubt; a comparison of the cutting speeds of a number of rotary rigs does not mean anything unless all were going at the same rate of speed and through the same type of formation. To make the thing complete, statements concerning all possible variables would seem desirable.

I want to ask Mr. Cartwright if he has had experience with the various casing protectors and has found that they made a difference in cutting speed, or in the time of going into the hole or coming out of it. Theoretically, they should speed the bit up a great deal. On the whole, as you go deeper it would seem that wall friction would become more and more a factor in absorbing the energy applied at the Kelly.

E. O. Bennett,‡ Ponca City, Okla.—Both of these machines are torque-limiting machines. They do not govern the pressure on the bit and unless used with proper care one can get just as crooked a hole as when drilling without their use. However, with proper intelligence a straighter hole should be drilled with an automatic machine than without.

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† Staff Geologist, The Gulf Companies.

‡ Chief Engineer, Marland Companies.

Big strides are now being made for improving the type of weight indicator. The type now in use, which is strung up on the dead line, depends upon a principle which, while accurate for light loading, is not suitable for heavy loads. The heavier the load, the nearer the cable upon which the indicator is fastened becomes to a straight line and the sensitivity and accuracy of the instrument diminishes.

The proper type, in my opinion, is one that at all times will weigh the actual load supported on the derrick top, and one that will not hamper pulling on the dead line when necessary in a great many cases. A few minutes may save many thousands of dollars by enabling the removal of the string from the hole where the cable is dead-ended on the calfwheel. Where the weight indicator is fastened to the dead line immediate pulling on this line, in case of emergency, cannot be started. It is common practice in the Mid-Continent area to have one end on the rotary draw works drum and the other on the calfwheel. The present type of indicator is good and serves a valuable purpose, but there is great room for improvement and I feel that it will only be a short time until we will all be using a type that will weigh the actual load at all times.

Underground Surveys of Oil Wells

By Alexander Anderson,* Fullerton, Calif.

(New York Meeting, February, 1929)

In many oil fields a great variation in the production of adjoining wells has long been observed, and a certain proportion of dry holes, situated between prolific producers, has been regarded as normal without thorough investigation as to cause. Similarly, an occasional prolific producer has been found in a part of a field where all other holes have proven disappointing.

Adjoining wells which showed an unreasonable difference in production have been surveyed, and the bottom of the poorest producer has been found to have lost sufficient vertical depth, through its drift, to diminish seriously its penetration in the oil zone. Again, the bottom of the good producer has been found to be more favorably situated by its migration up structure.

Surveying of wells in California fields has shown many instances where the dry hole has drifted far off the structure to such a degree that no amount of deepening could ever convert it into an oil well. In other cases, edge wells have been found to drift into the field.

At this time, in California, the surveying of oil wells is beginning to be accepted as a routine part of operating procedure. Some operators are surveying all of their new wells and, in some of the recently discovered fields, this practice is providing invaluable assistance in methodical development.

The information that has been obtained from the surveying of many wells has convinced most operators that it pays to give careful attention to the drilling of wells. Crews are now usually cautioned to avoid reckless competition with each other. Whereas, formerly, certain companies demanded a large footage from their drillers, they now issue orders that a very moderate speed in drilling shall be maintained and that every care be taken to avoid practices likely to cause excessive deviation of the hole from vertical. As a result of these new instructions to drilling crews, a distinct decline in the average drift of the wells drilled by these operators has taken place and fewer dry holes are being drilled from good locations.

To the petroleum engineer and the geologist, oil-well surveys provide the necessary data required for the construction of the correct cross-

* Mining and Petroleum Engineer.

sections and make it possible to work out true correlations. Where repressuring of sands is being considered, an exact knowledge of the position of the wells at bottom is extremely valuable. To those responsible for running casing, the survey provides information showing at which points the casing is liable to stick and enables an intelligent reaming program to be carried out. To those who are contemplating the financing of a partly drilled well, a survey will show whether the well is taking a favorable direction. To the wildcatter, a survey will show whether the test well is reasonably vertical or whether it has drifted off structure and does not constitute a test.

Where a considerable number of dips have been obtained from cores distributed throughout the depth of the well, and where the survey shows that the well has attained a high inclination, or has a moderate inclination and a considerable change in direction, it is sometimes possible to determine the amount and direction of dip of the strata. The surveying of a discovery well may disclose valuable information as to the probability of other wells making similar production.

The text accompanying the tables and figures of this paper, is of a very incomplete character. Although the writer has been exclusively engaged in surveying oil wells for several years, he believes that many of the features and uses of oil-well surveys could be better dealt with by some of the men whose business it is to utilize them in their work. No complete reproductions of any surveys have been included in this paper but several[1] of the writer's surveys have been published.

Survey Apparatus

The apparatus employed in making the surveys mentioned in this paper comprises a photographic recording mechanism enclosed in a water-tight casing and adapted to be run into the well on the end of a string of drill pipe or tubing. With the standard apparatus, 88 consecutive readings for inclination and direction of inclination may be taken during one lowering into the well. One reading is generally taken after each stand of pipe is lowered, or say, about 12 readings per 1000 ft. of hole. Usually, 12 readings per hr. are taken in a well. Vertical angles are read to approximately the nearest 10 min. and directions to about 3°.

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[1] F. M. Smith: Surveying Oil Wells with Anderson Apparatus. *Eng. & Min. Jnl.* (1926) **121,** 241.

F. S. Hudson and N. L. Taliaferro: An Interesting Example of a Survey of a Deep Bore Hole. *Bull.* Amer. Assoc. Petr. Geol. (1926) **10,** 775.

A. Anderson: Underground Survey of World's Deepest Well. *Oil Age* (Sept., 1926).

D. C. Roberts: Long Beach Oil Field. *Summary of Operations California Oil Fields* (May, 1928) **13,** No. 11, 13th Annual Rept. State Oil and Gas Supervisor.

A full description of the apparatus and methods will be published at a later date when patent office drawings are available.

The writer has surveyed nearly 2,000,000 ft. of rotary hole. In the surveying of this footage the apparatus was run in about 800,000 ft. of open hole. On no occasion has the apparatus stuck, nor has any tendency to stick ever been observed. It is supplied with holes permitting circulation and occasionally the mud in a well has been reconditioned by circulating after the apparatus has reached bottom.

Operators often check the inclination of their wells with the acid bottle and by observing changes in the apparent dip shown by cores. It has not always been found to be safe to run a bailer into open hole for the purpose of taking an acid bottle reading.

Drift and Inclination of Rotary Holes

The maximum, minimum and average values of drift and inclination over a total of 1,158,542 ft. of rotary hole are shown in Table 1. The

TABLE 1.—*Drift and Inclination of Oil Wells*

Data from underground surveys of 255 rotary-drilled holes mostly in California 1,158,542 ft. of hole and 13,150 individual survey readings.

A, measured depth; *B*, horizontal distance from mouth to bottom of hole; *C*, inclination from vertical at listed depth; *D*, total drift from vertical down to listed depth.

In case of a well drifting in same direction from mouth to bottom *B* and *D*; would be equal.

No. of holes	A. Depth in feet	B. Horizontal distance from mouth to bottom of hole. In feet.			C. Inclination of hole from vertical in degrees & feet per 100 ft.			D. Amount of drift from vertical in feet.		
		Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average
255	500	37	0	8.7	8° 20′ 14.5 ft per 100	0° 00′	2° 09′ 3.8 ft per 100	114	0.0	10.6
255	1000	131	2	30.2	15° 30′ 26.7 ft per 100	0° 00′	3° 05′ 5.4 ft per 100	131	0.0	34.4
243	2000	455	9	89.2	34° 15′ 56.3 ft per 100	0° 10′ 0.3 ft per 100	4° 05′ 7.1 ft per 100	457	1.5	104.5
219	3000	845	9	119.5	32° 15 53.4 ft per 100	0° 30′ 0.9 ft. per 100	6° 42′ 11.7 ft per 100	850	47.0	204.9
163	4000	1036	6	236.5	40° 15′ 64.6 ft per 100	0° 30′ 0.9 ft per 100	9° 00′ 15.6 ft per 100	1285	77.6	307.7
104	5000	1752	29	396.8	52° 00′ 78.8 ft per 100	0° 30′ 0.9 ft per 100	15° 44′ 27.2 ft per 100	1815	91.0	515.9
38	6000	2200	74	589.4	65° 15′ 90.8 ft per 100	2° 30′ 4.4 ft per 100	22° 25′ 38.1 ft per 100	2228	357.0	793.1

inclinations and drifts shown as maximum are limited because the survey apparatus was originally designed to record inclinations up to 54° from the vertical and was later modified to measure inclinations to 65° from vertical. As a consequence, the largest inclination from the vertical is shown as 65° 15 minutes.

In about a dozen of the rotary holes included in the table, the survey ceased after the holes had reached an inclination between 54° and 65° from the vertical and the inclinations and directions of the lower portions of these particular wells are, therefore, not known. Some of these holes

were uniformly increasing in inclination with depth, and it seems certain that several of them became horizontal or pointed upward at bottom.

In one instance where a bailer could not be run to the bottom of a rotary hole when surveyed, the hole was found to have an inclination of 60° from vertical at the point where the bailer had stopped. This well was increasing in its inclination and the operator judges from the cores obtained that it probably reached a horizontal position. The

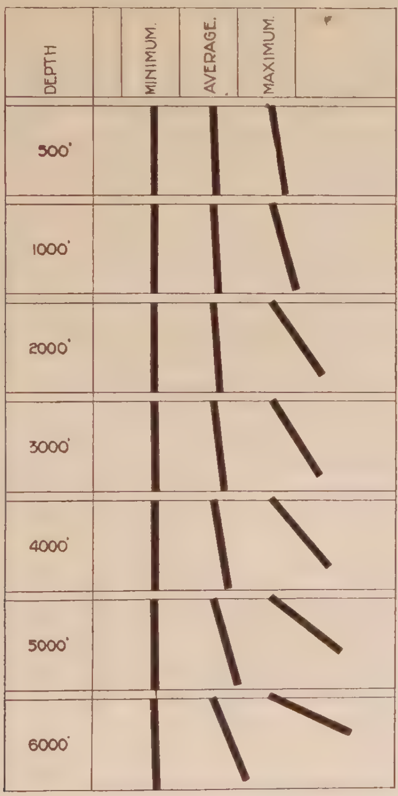


FIG. 1.—INCLINATIONS OF OIL WELLS FROM VERTICAL; CHART OF FIGURES OF COLUMN C OF TABLE 1.

survey showed that the hole had drifted completely off the structure and the point where the survey stopped was already many hundreds of feet outside the limits of the field.

The figures of column C, Table 1, are presented graphically in Fig. 1. The increase of inclination with depth shown in the maximum column is interesting, but should not be interpreted without further explanation. In compiling Table 1, it so happened that the maximum inclination at each listed depth provided the apparently logical sequence so easily grasped by inspection of Fig. 1, but it should be noted that a considerable

number of wells, which were finished at intermediate points between the seven listed depths, attained very much greater inclinations than the table indicates: in several instances wells finished at depths between 3000 and 6000 ft. attained an inclination of 50° or more.

Influence of Bad Wells on Table 1

A certain proportion of the surveys shown in Table 1 were made to investigate wells which had proved disappointing. Most of the disappointing results were due to excessive drift of the holes. Owing to the inclusion of an undue proportion of bad wells, the averages shown, both for drift and inclination, are probably about 25 per cent. greater than the true averages that might be expected from a similar number of wells chosen at random in the same fields, and drilled at about the same date.

In spite of the fact that the averages of Table 1 are higher than normal for the particular fields from which they were drawn,[2] there are fields in California where the average drift is probably greater, and there are yet other fields where the drift is undoubtedly a good deal less.

Loss in Vertical Depth Caused by Drift

Table 2 was compiled from the same wells as Table 1, and includes a similar footage of rotary hole. To make it strictly comparable with

Table 2.—*Loss in Vertical Depth Caused by Drift in Rotary Holes*

Measured depth in feet		Loss in vertical depth in feet		
From	To	Maximum	Minimum	Average
1000	2000	20	0.7	3.4
2000	3000	130	1.0	29.4
3000	4000	335	0.6	39.8
4000	5000	370	4.0	38.4
5000	6000	542	7.0	115.6
Over	6000	620	6.0	169.7

Table 1, the difference between the measured depth and vertical depth of each well at 1000, 2000, 3000 ft., etc., should have been tabulated, but this was not done: in compiling Table 2 only the difference at bottom between the measured depth and the vertical depth of each well was taken.

It will be noted that the average loss in depth of wells finished at between 3000 and 4000 ft. is 39.8 ft., as compared with 38.4 ft. in the wells finished at between 4000 and 5000 ft. The apparent contradiction in these figures is due to the influence of a few wells of exceptionally large drift finished at between 3000 and 4000 feet.

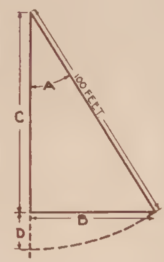
[2] Seventy per cent. of the footage of this table was surveyed in the Signal Hill field, Los Angeles County, California.

Relation between Drift and Depth

Table 3 shows the relation between the three sides of a right-angle triangle in which the hypotenuse represents a portion of an inclined hole. Without the assistance of a table of this kind it is not easy to realize the

Table 3.—*Relation between Sides of a Right-angle Triangle, Showing Drift and Vertical Depth*

A. Inclination of hole from vertical	B. Horizontal drift per 100 ft. of hole	C. Vertical depth drilled per 100 feet of hole.	D. Loss in vertical depth per 100 ft. of hole.
0°	0.0	100.0	0.0
5°	8.7	99.6	0.4
10°	17.4	98.5	1.5
15°	25.9	96.6	3.4
20°	34.2	94.0	6.0
25°	42.5	90.6	9.4
30°	50.0	86.6	13.4
35°	57.4	81.9	18.1
40°	64.3	76.6	23.4
45°	70.7	70.7	29.3
50°	76.6	64.3	35.7
55°	81.9	57.4	42.6
60°	86.6	50.0	50.0
65°	90.6	42.3	57.7
70°	94.0	34.2	65.8
75°	96.6	25.9	74.1



simple facts shown in it; for instance, when a well is drifting horizontally 90.6 ft. with each 100 ft. drilled, it is still making a vertical penetration of 42.3 feet.

The drift of a well is not necessarily indicative of its vertical depth. A deep well may attain a considerable drift because it reaches an inclination such as 5° a few hundred feet below the derrick floor and continues to have approximately the same inclination to bottom. Another well may remain nearly vertical to a much greater depth and may then attain a similar drift because a part of the hole near bottom has a high inclination. The figures of Table 3 show that a well with a uniform inclination of 5° will only lose vertical depth at the rate of 0.4 ft. per 100 ft. of measured depth, whereas a part of a well with an inclination of 30° loses 13.4 ft. per hundred. The loss in vertical depth in 100 ft. of hole, which is inclined at 30° from the vertical is, therefore, equivalent to the loss in vertical depth of 3350 ft. of hole which is inclined at 5° from the vertical.

Influence of Loss in Vertical Depth on Correlations

Taking an extreme case from Table 2, where one well is shown to have lost 335 ft. in vertical depth at a measured depth between 3000 and 4000 ft., it is evident that any correlation based on the assumption that the measured depth of the well corresponded to its vertical depth would

usually be at least 335 ft. out. However, in most cases, the error in correlation would generally be very much greater than 335 ft. because, to attain a loss of 335 ft. in depth, this well drifted 966 ft. from the vertical. For purposes of correct correlation, the position of the bottom of the hole must be taken into account and, if a deepening or redrilling job is being considered, the inclination and direction of the hole at bottom are also important factors.

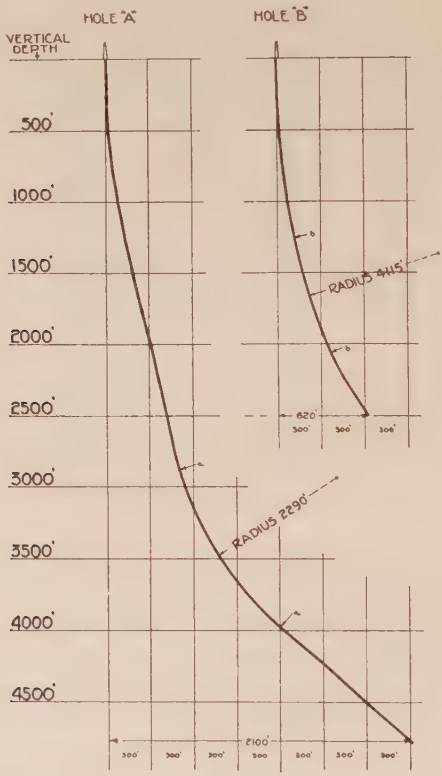


FIG. 2.—VERTICAL PROJECTIONS OF TWO ROTARY HOLES WITH LARGE DRIFT.

CURVATURE OF ROTARY HOLES

Severe kinks and bad places, where a sudden large change in inclination takes place in a rotary hole, are occasionally shown by a survey. To bring out the full detail of these parts, survey readings must be taken at short intervals. The most interesting features of curvature in rotary holes are, however, the moderate and continued bends which are mainly responsible for developing great drift and inclination in wells.

Holes *A* and *B* in Fig. 2 are holes of large drift, and neither of them hows any great change in direction of drift. Each of these wells was

projected on a vertical plane which included the mouth and the bottom of the hole: the projections are, therefore, practically exact facsimiles of the hole. In each of these wells there is a portion of the hole, *a-a* in hole *A* and *b-b* in hole *B*, in which the curvature is constant; each of these parts is, therefore, a segment of a circle.

The radius of the part *a-a* of hole *A* is 2290 ft., and the radius of the part *b-b* of hole *B* is 4115 ft. The curvature of *a-a* is equivalent to a rise *R* of 1.08 in (0.09 ft.) in a length of 40 ft., or say a length equivalent to about two joints of drill pipe (Fig. 3). The great drift of hole *A* is mainly due to the increase in inclination which takes place in *a-a*. Below *a-a* the inclination remains nearly constant.

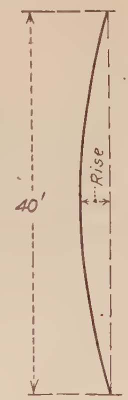


Fig. 3.—Curvature of hole where rise in length of 40 ft. for wells *A* and *B* is 1.08 and 0.6 in., respectively. (Figure not to scale).

In hole *B* the curvature of the part *b-b* also plays an important part. The radius of this segment is 4115 ft. and the rise in a 40-ft. length of hole is, therefore, 0.6 in. (0.05 ft.) (Fig. 3).

Holes *A* and *B* are examples of wells which are in perfect mechanical condition, and which have no severe bends, kinks, or bad places in them. The inclinations and drifts attained by both of these wells are due to continued slight increase in inclination. To their drillers, both of these wells appeared to be perfect, and neither of them gave any indication of drift or curvature to the men on the derrick floor. Table 4 shows seven of the 62 survey readings taken in well *A*, Fig. 2.

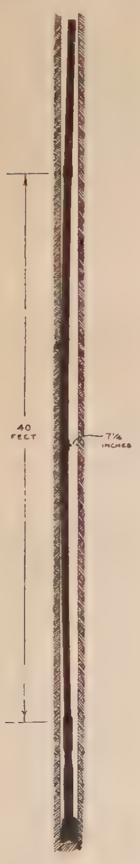


Fig. 4.—Scale drawing of 6-in. drill pipe within a 15-in. hole.

Fig. 4 is a scale drawing showing a length of 6-in. drill pipe inside a hole 15 in. in dia. The diameter of the tool joints is 7¾ in. When a tool joint is resting against one side of the hole, as, for instance, the tool joint at the top of the first joint of pipe above the drill collar in Fig. 4, the space between the 7¾-in. dia. tool joint and the wall of the 15-in. dia. hole is 7¼ inches.

Why is the curvature of hole *A* only 1.08 in. in 40 ft. of hole when a very much larger space between the tool joints and the wall of the hole is available? In Fig. 4 the free space between the wall of the hole and the tool joint is seen to be 7¼ in. and, although the dimensions of Fig. 4 are probably not the same as the relative dimensions between hole diameter and drill pipe in hole *A*, it is

TABLE 4.—*Survey Data on Well A*

Reading No.	Measured Depth, Ft.	Vertical Depth, Ft.	Inclination from Vertical	Direction of Inclination	Total Drift from Vertical, Ft.
7	551	549	8° 40′	S 48° 48′ E	38.06
12	993	985	9° 10′	S 31° 54′ E	109.60
24	2057	2019	14° 00′	S 19° 40′ E	359.30
35	3033	2968	16° 00′	S 18° 28′ E	589.19
46	4008	3807	40° 00′	S 3° 23′ W	1015.51
57	4983	4454	46° 00′	S 8° 18′ W	1805.56
62	5379	4713	48° 00′	S 6° 52′ W	2100.00

obvious that the space available in the latter was much greater than that utilized in the curvature of the hole.

The greatest continuous curvature that the writer has observed in a rotary hole amounted to 1.44 in. (0.12 ft.) in a length of 40 ft. of hole. This is approximately equivalent to an increase in inclination of 1° with each 30 ft. of hole or, say, an increase in inclination of 3° per 90-ft.

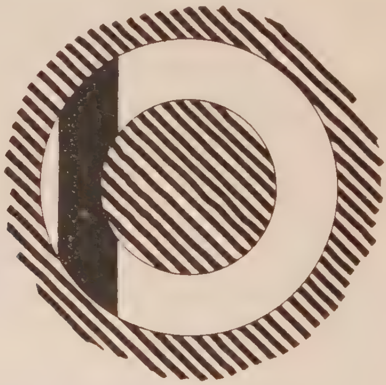


FIG. 5.—CROSS-SECTION OF ROTARY HOLE SHOWING ANNULAR CUTTING BY FISHTAIL BIT.

stand of pipe. Apparently, the relative proportions of the diameter of the tool joints and drill pipe is not the only factor, or even the most important factor in the determination of the curvature of a rotary hole.

When weight is placed on the drill bit in a vertical hole, the drill pipe is obviously cramped down in the hole and each tool joint finds support against the walls of the hole. When drilling commences, it seems probable that the drill pipe is wrapped around the interior of the hole in a spiral form and that the spiral rotates as a whole and, at the same time, the pipe itself rotates.

Occasionally, a fishtail bit will become flattened against the side of the hole and the rotation of the pipe itself will be stopped while the rotation of the pipe as a spiral will continue. When this occurs, the fishtail bit

will cut an annular hole, leaving a core standing up in the center of the hole. The outside of the bit soon grinds away to a segment of a circle and the projecting core wears a groove in the inner side of the bit (Fig. 5). Of course drilling cannot continue with the bit in this position and a twist-off will soon take place. This incident is mentioned here because it proves a case of spiral rotation of the drill pipe.

Influence of Torsion in Drill Pipe on Curvature of Rotary Holes

It is commonly stated that the drill pipe sags down onto the lower side of an inclined hole and thus raises the end of the bit to make the hole go farther and farther out of vertical. The writer suggests that the drill pipe tends to take a spiral form and that this spiral, as a whole, rotates like an attenuated corkscrew within the hole and that the pipe, therefore, does not lie in the bottom of the hole. If this is the case, it may help to explain why the usual curvatures found in rotary holes are so very much more moderate than they might be expected to be if the pipe lay in the lower side of the hole.

Drift of Rotary Holes Relative to Dip of Strata

Where the dip of the strata does not exceed 10°, it has been noticed that in some fields there is a tendency for wells to butt into the structure. Sometimes, for this reason, a well may end up several hundred feet higher on the structure than the position of the derrick would indicate. Instances of wells butting into the structure have been found even when the dip was known to be 60°, and very interesting geologic information has been obtained from cores taken from wells of this kind which traveled into and across a structure at a very flat inclination.

As the dip of the strata gets higher, the proportion of wells which butt into the structure usually becomes smaller. Where the dip is around 25°, many wells may follow the direction of the strike and many may follow a general down-dip direction. When not too near the edge of the field, a carefully drilled down-dip well may make a good producer, but if one of these wells is carelessly drilled, it will frequently be forced completely out of the field and cores taken from such a well may show vertical striation because the well has become parallel with the strata.

When a hole starts to drift off structure and attains a considerable inclination from vertical a few hundred feet below the derrick floor, it is usual to find that the direction of the drift is maintained. The plan view of a well of this kind is generally very nearly a straight line, and the drift is frequently enormous.

Wells, which start out with a drift along the strike, often change direction and may either butt into the structure or run down dip. In

some parts of certain fields, adjoining wells show very similar inclinations and direction of drift. In these localities, redrilling may succeed in lessening the amount of drift but is apt to fail to alter materially the direction of drift.

In other parts of the field there may be a critical depth at which a well will either make a change of direction up or down structure. Under such conditions, when the hole is redrilled from the critical depth, it may take a more favorable direction and a good producer is often obtained from a previously hopeless hole.

[For discussion of the above paper see page 45.]

Acid Bottle Method of Subsurface Well Survey and Its Application*

By E. H. Griswold,† Ponca City, Okla.

(New York Meeting, February, 1929)

The surveying of oil wells has in recent months become a common practice in the deep fields of the Mid-Continent area. Borehole surveys have been made by mining companies for many years, but the introduction of such methods into the oil fields has been delayed until the past few years, because the value of survey data was not fully appreciated.

The acid and gelatin bottle methods of obtaining the angle of deviation and the floating compass method of obtaining the direction of horizontal drift have been in use for more than 20 years. A photographic recording instrument consisting of a plumb bob, magnetic needle and electrically operated camera was devised and used in the Rand mining fields of South Africa prior to 1912.[1] Another and improved photographic instrument, depending upon orientation of the drill pipe instead of polar magnetism for direction, has been invented and used. The acid bottle method has also been used in conjunction with oriented drill pipe.[2] The magnetic compass is not reliable for oil-well work because of the unsymmetrical attraction of the needle to the well casing and possible magnetic formations. Many engineers also concur in the opinion that orientation of the drill pipe from instrument to surface will be inaccurate because of the torque exerted between the drill pipe and walls of the hole, causing the lower sections of pipe to twist. When it is considered that 4000 ft. of 6 in. drill pipe has approximately the same slenderness ratio as 6 ft. of silk thread, such twisting effects can be readily visualized. The gyroscopic compass has been suggested for use in direction finding, but the high cost of such instruments will prohibit their use, except in special cases.

Due to the lack of accurate direction-finding instruments, almost all of the survey work in the Mid-Continent fields has been of the acid bottle method alone.

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* Presented by permission of Marland Production Co.

† Production Engineer, Marland Production Co.

[1] J. J. Hoffmann: Recent Practice in Diamond Drilling and Borehole Surveying. *Bull.* Inst. Min. & Met. (April 18, 1912); Peele's Mining Engineers Handbook (1918) **1**, 371.

[2] E. E. White: Surveying and Sampling Diamond-drill Holes. *Trans.*, A. I. M. E. (1912) **44**, 69.

Acid Bottle Well Survey Apparatus

When surveying wells through the casing or open hole, the bottle container is latched securely to the bottom of or between two joints of 3 or 4-in. pipe, with a bail connection on the top for attaching to the sand line. Fig. 1 shows the construction of one such instrument which has proved very satisfactory. The bottle container must be pressure-tight, in order to prevent collapse of the bottle from fluid pressure and also, the design should be such that bottles may be changed without loss of time or excessive jarring.

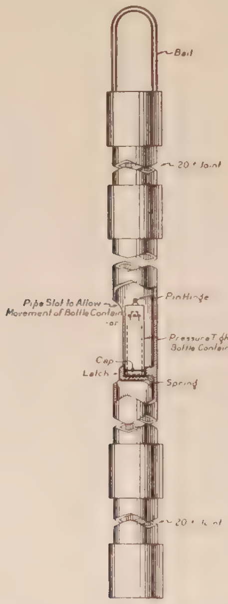

Fig. 1.—Acid bottle well survey instrument for running through casing.

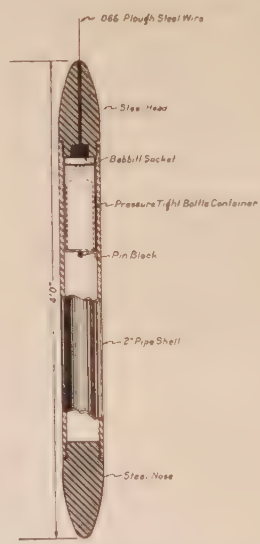

Fig. 2.—Acid bottle well survey instrument for running through 6-in. drill pipe.

Fig. 2 shows an instrument used to survey wells while drilling by the rotary method, without removing the drill pipe from the hole or requiring the interruption of mud circulation, except when running in or pulling out the instrument. A steel wire is used as a hoisting line, the spool being power-driven from the cathead. In this type of device it is important that the outside diameter of the instrument be equal to, or slightly greater than the difference between the inside diameters of the drill pipe and tool joints, so that the alignment with the pipe will be preserved. It is, of course, necessary to discard the drill pipe float valve when using this method of survey.

The bottles used vary from $1\frac{1}{2}$ to $2\frac{1}{2}$ in. in dia. and should be uniform inside and outside to facilitate reading. A 1:1 solution of hydro-

fluoric acid and water is used to secure a clear etch within approximately 10 minutes.

Procedure

The operation consists of filling a bottle about half full of the acid solution, placing it in the instrument which is then lowered to the desired depth and allowed to stand for 10 min. before pulling out to change bottles for the succeeding run. It is customary to take a bottle reading at intervals 200 to 400 ft. apart unless sharp bends justify closer observations. A new bottle is used for every reading. The depths may be measured with a friction cyclometer thus speeding up the operation without exceeding the limits of survey accuracy.

The angle of inclination of the hole may be clearly seen in the etched mark on the bottle where the surface of the acid has been. The angle between the side of the bottle and the etched mark can be read directly with a goniometer or calculated by measuring the distance from the low to the high side of the etch and the inside diameter of the bottle. The direct reading method is preferred as it is well within the limits of accuracy involved. Capillary effects between the acid and bottle make it necessary to correct the readings, especially when large angles are obtained. This error due to capillarity, may be as high as 5° and will vary with the concentration of the acid, diameter of bottle and degree of inclination. It is advisable to determine by experiment the proper capillary correction curve for the materials used, rather than to rely on theoretical calculations of viscosity and surface tension of the materials.

Calculation of Drift and Depth

The total amount of lateral drift and the difference between the measured length of the hole and the actual depth below the derrick floor may be obtained by trigonometric calculations from the angles, assuming each segment of length to form a relatively straight line through the point of reading. The calculations may be greatly simplified with the use of a set of traverse tables, by designating vertical distances as latitudes and horizontal distances as departures.

Direction of Deflection

Fig. 3 shows graphically in two dimensions the result of a survey of a typical well of the Seminole area. It should be noted that the abscissas are designated as total horizontal deflections and are not necessarily all in one direction. However, from the gentle bends and uniform slopes of most wells surveyed so far, it appears reasonable to expect that deviation is at least in the same general direction, as a change in direction, with respect to the strike of the formation, would cause sharp changes in the angles of inclination. The compass surveys taken from core drill holes

in nonmagnetic mining regions substantiate the theory that deflection is all in one general direction and also indicate that when steeply dipping strata are penetrated, the deflection is down-dip, while with gently dipping strata the deflection is toward the up-dip side.

Information Obtained by Acid Bottle Method

Four definite facts are determined by the acid bottle method of survey as follows:

1. Whether or not a hole is crooked.
2. If so, at what depths and at what angle from the vertical.
3. The total possible horizontal drift.
4. The exact depth of the hole compared to the measured length of hole drilled.

Facts 1 and 2 are of somewhat doubtful value to the producer, as they can only be used in comparing the relative straightness of holes drilled by different methods, in an attempt to devise means of drilling straighter and cheaper holes. It is not thought possible to drill even approximately straight holes without sacrificing much of the speed of modern rotary drilling, although considerable improvement is to be expected. The knowledge of the course of a hole may be of some value in reaming the hole prior to running casing or in spacing sucker rod guides, but sufficient information to judge these conditions can be obtained by intelligent observation of drilling and producing equipment. The ease with which casing runs in a hole or the manner in which cable tools run are not good criteria for determining the amount of drift or deviation. A 4000-ft. string of 9-in. A. P. I. casing was run without difficulty in a hole drilled with an 11-in. rock bit and known to have inclinations of as much as 25° from vertical. Cable tools have operated satisfactorily at angles of more than 30°.

Facts 3 and 4, relating to maximum possible drift and exact vertical depth of hole, are of the utmost importance to the producer, subsurface engineer and geologist. Errors of more than 200 ft. in total depths are common in deep holes due to the difference between the measured length of the hole and the actual vertical depth below the level of the derrick floor.

Utility of Method

Leases may be bought or sold, locations made and wells drilled because of information as to how high or low certain nearby wells may have encountered the sand. A knowledge of the depth to which a well can be drilled into the sand without danger of encountering water, is often necessary in order to obtain the maximum production. The use of well records in determining water horizons entails considerable risk unless survey corrections are applied.

In many cases offset wells which seemingly had approximately the same subsea level depths to the sand were found to have as much as 100 ft. difference in actual sand elevations. In other cases, wells, which appeared to run 200 ft. lower than nearby wells, have been found to be approximately equal and sometimes even higher in actual sand elevation.

One well surveyed had a large but temporary initial gas production and was apparently located in a short syncline when contoured in respect

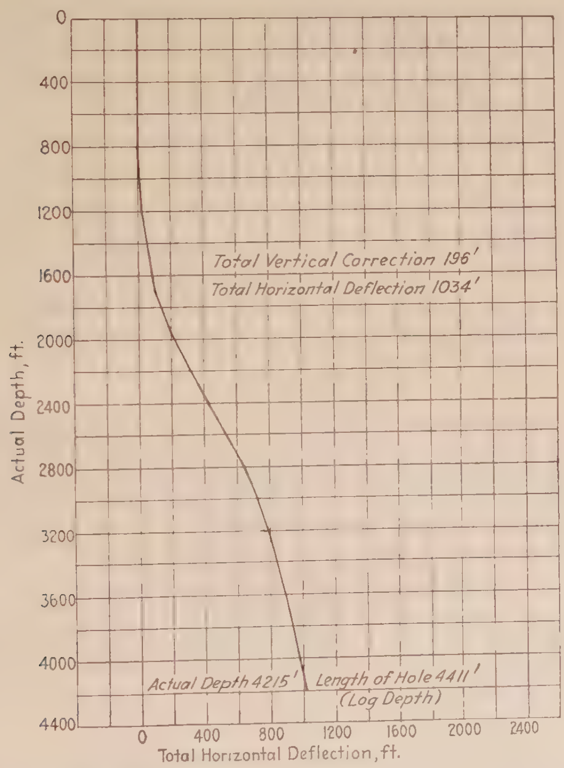

Fig. 3.—Results of survey of typical well in Seminole area.

to surrounding oil wells. The large gas production was attributed to unusual sand conditions until the well was surveyed, two years after completion, and found to require a vertical correction of 55 feet.

No reasonably accurate subsurface map of the recently drilled deep fields of the Mid-Continent area can be made from well logs without survey corrections, although structures drilled before the advent of the modern slush pumps and high boiler pressures, often contour within reasonable limits.

Many of the faults and structural sinks supposedly encountered in the Seminole producing areas are now being disproved and many data, compiled and worked up at considerable expense, are invalidated unless checked by survey corrections. It is certainly inconsistent to consider topographic elevations if the vertical errors due to drift are to be disregarded.

By inscribing each well with a circle, the radius of which is equal to the maximum horizontal deflection of the well, and applying the vertical correction to successive points within the circle, the most logical location of the contours can be determined with considerable accuracy.

The practice of accurately staking well locations is only of value in obtaining a symmetrical and systematic layout of surface equipment as spacing programs have no actual effect on the locations of deep wells other than to limit the total number of wells drilled within the area of a field.

The prolonged life of some wells and the drainage interference of others are now usually explained by crooked holes rather than by exceptional sand conditions. Several cases are on record where wells located 660 ft. apart on the surface have come together, usually requiring the abandonment of both holes.

DISCUSSION

[Includes also discussion of paper by Alexander Anderson, page 30.]

H. W. Hixon, New York, N. Y.—Was anything specific done in rotary drilling to prevent tilting of the rods against the wall; the use of a wooden collar, for example?

C. V. Millikan,* Tulsa, Okla.—Reamers are often used above the drill collar but this would prevent tilting only in the bottom few feet of the drill stem.

H. W. Hixon.—The collar can always be grooved. If, for example, the wooden collar is two strands of rod away from the bit, that will prevent the rods from getting against the wall of the hole and will hold the bits straight. The diamond-drill people show a contrivance of that kind but it is always down right at the top of the core barrel, and it is only 15 ft. or so long, which is too near the bit. It must be farther away from the bit to accomplish anything.

C. V. Millikan.—That is true. We must get away from the bit, because if there is a deviation of only 1 in. in 100 ft., and that is accumulated down to 5000 ft., the hole will be off considerably.

F. H. Lahee,† Dallas, Tex.—A reamer above the bit and another one or two joints above the bit may help to prevent crookedness. We are using instruments for measuring weight of the drill stem, so that we can reduce the tremendous pressures which have been applied to the bit. Also, other efforts are being made in a mechanical way to cure this defect.

C. V. Millikan.—We are now using a much longer shank on the rock bits than were used a few years ago, especially during the development of the Tonkawa field in 1922 24. The contractors all thought that the shorter the shank on the bit

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† Chief Geologist, Sun Oil Co.

the less danger there was of getting hung up, but now they are coming to the conclusion that the longer the shank, the less danger there is. They are coming quite commonly to 4 and 5-ft. shanks, and one contractor is making an effort to get a 12-ft. shank on a rock bit. These are nearly all run with reamers directly above the bit.

Another piece of equipment I saw (I know nothing about its practicability, though I saw nothing wrong with the idea) is using a spiral stem. The particular stem that I saw was about 20 ft. long and 12½ in. dia. with regular rotary tool joints welded on each end, a joint of 1½-in. pipe running from the upper tool joint around the spirals to the lower tool joint in order to get circulation. By using such a spiral stem to the full diameter of the hole, they still have ample area for circulation.

V. C. Warren,* Los Angeles, Calif.—Have you found in the recent surveys of holes what Mr. Anderson seems to find — that a hole may make a complete circle? Not necessarily go off of formation, but have a corkscrew motion and come back almost directly below the original starting point?

C. V. Millikan.—We have never surveyed a hole as to direction.

V. C. Warren.—I saw that in one of the deeper holes in Ventura County. It struck a number of different formations going down, and that hole was most peculiar. It went in every direction but finally came back pretty near home. Of course, it had lost some distance in depth.

A. W. Ambrose,† Bartlesville, Okla.—In the Mid-Continent, I believe all of the surveys of crooked holes have been limited to the use of the acid bottle, which gives the deflection but not the direction. Mr. Anderson's method gives the direction. I believe Mr. Griswold's results were based on acid-bottle surveys.

R. R. Brandenthaler,‡ Bartlesville, Okla.—An interesting drilling experiment for the purpose of determining factors affecting the deviation from the vertical was conducted in the Mid-Continent during the past year. While drilling with a rotary the usual procedure of "romping" on the bit was not permitted. A weight indicator was installed on the drill pipe and the weight on the bit reduced. The rate of mud circulation was also controlled. At a depth of 2000 ft. it was found that the hole was very crooked. The well was then plugged back 1000 ft. and drilling resumed in the usual manner; that is, by allowing more weight on the bit. The new hole was considerably straighter. This, of course, was contrary to our ideas as to the effect of "romping" on the bit.

J. R. Suman, Houston,§ Tex.—There are a couple of points that should be brought out in this connection, I think. One is the difficulty with this hole-measuring from a legal standpoint. In Texas we have been very much troubled about measuring holes. We are using the acid bottle because we only want to know the dip. We measured a number of holes, and the maximum deviation from the vertical was 14°. That is in the Mexia fault district, fairly hard formation.

In the Gulf coast, we think the holes are almost vertical. The reason is that the formation on the Gulf Coast is soft and unconsolidated, and we arrive at this conclusion from the small amount of pumping trouble we have there.

The inference that you can draw from this is that in the unconsolidated sediments the hydraulic effect tends to keep the drill stem vertical all the time to the making of

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‡ Petroleum Engineer, Petroleum Experiment Sta., Bur. Mines.

§ Director, Production Dept., Humble Oil & Refining Co.

straight hole, and we find in the Gulf Coast that the holes drilled fast, where you can make the holes fast, are straight. Sometimes we have drilled 1200 or 1300 ft. per day and the stuff just melts away from the drill stem; therefore the holes are more likely to be vertical.

L. G. E. Bignell,* Tulsa, Okla.—Is there any difference in the size of the pumps? Does that have anything to do with the hydraulic effect?

J. R. Suman.—I do not think so. We are using the largest we can get. In the Boggy Creek field measurements the maximum deviation was 14°. They vary all the way from 8° to 14° and it does not seem to make very much difference as to the pumps used.

Another matter is the legal aspect. The more I study the law of the land, the more confused I become. We have a law that oil and gases and fuel substances belong to the person who happens to capture them, which means that a man who has 5 acres on top of a 2000-acre structure can go ahead and develop it and waste the gas at will and be protected by law. He is a pirate, nothing less. Therefore we ought to have a similar law that no matter where the bottom of the hole is, the oil you get out of it is yours and the royalty belongs to the man on whose lease you start the hole. That is no more asinine than the other law I mentioned and no different from the apex law which mining men are enjoying, and seriously speaking, I believe that before we go very far in this measuring of holes, particularly if we use both components of measurements, we are going to be faced with some very serious lawsuits.

H. W. Hixon.—I can see that if such a law were passed you could drill a hole at an acute angle and drill under the other fellow's property at the start, and I do not think that would help matters or avoid litigation.

F. H. Lahee.—I think Mr. Suman is overoptimistic. I think possibly he is also very lucky, because I know we have measured depths of holes on the Gulf Coast which were found to be as much as 26° off the vertical at 4000 or 5000 ft. My general feeling on the whole problem is that the world would never advance if we always looked ahead for legal trouble in connection with any invention that is going to be made or any progress towards better production methods or manufacturing methods or anything of the kind. We simply have to face the problem and try to correct the crookedness of the holes and let the legal aspect take care of itself. Simply to refuse to survey holes for their true position on the chance that there may be legal trouble leaves us in the back ages.

There are two ways of looking at this problem. In the first place, crookedness of holes causes a great deal of expense in twist-offs, difficulties in drilling, wear on the rods in pumping wells, and in other mechanical ways. In the second place, certainly sometimes a well that is properly located on a structure at the surface runs off the structure at depth, so that the company that should get the oil does not get it.

In the third place, there is the geological aspect. The vertical error was mentioned by Mr. Griswold. The horizontal component is the thing that leads us to the legal aspect. Certainly, if we are taking cores from the bottom of a hole that is off like that one in Fig. 3 (page 45) our maps are in error in many cases. Furthermore, there are cases where the bedding dips strongly enough to show up in the cores, and in order to find the direction in which it dips it is necessary to have the angle of inclination of the hole as well as its direction of inclination to determine the orientation of the core in the hole where it was taken. I look upon it as very important to develop a method by which we can take oriented cores, determining their exact position with relation to the surrounding country.

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* Sales Engineer, Parkersburg Rig & Reel Co.

A. W. Ambrose.—There is no question but that it is a factor in geologic studies. I know in the Seminole district the first maps made indicated much faulting. Probably many supposedly low wells inside a producing area were actually not so low but were indicated as low because of the crookedness of the hole.

R. J. Riggs,* Bartlesville, Okla.—Crookedness is very important and should be taken into consideration in all subsurface work. Using corrected figures, we find that most of the almost absurd irregularities are wiped out, although I believe in Seminole there are some unexpectedly low holes which cannot be accounted for by crooked holes. I believe a map which represents the facts more accurately can be made by discarding holes which we believe to be unusually crooked.

V. C. Warren.—A question was asked about crooked holes in California. We have very steep dips and hard shells that probably account in some respect for that. I think you will find that most of Mr. Anderson's extremely crooked holes have been taken out of town-lot fields. They do romp on them and do not use any care at all. I think we will find that that probably is the answer to our story.

J. W. Dunn,† Pittsburgh, Pa.—What about the speed of rotation of the drill pipe? Do you have any data on that?

C. V. Millikan.—I have no information on that; that is, as it affects the deviation of the hole.

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* Chief Geologist, Indian Territory Illuminating Oil Co.

† Petroleum Engineer.

Pumping Deep Wells in the Seminole Field, Oklahoma

By M. J. Kirwan* and K. A. Covell,† Bartlesville, Okla.

(Tulsa Meeting, October, 1928)

This paper covers a brief discussion of pumping 38° to 41° gravity oil from Wilcox sand wells ranging in depths from 4000 to 4900 ft. in the Seminole field, Oklahoma.

As recently as a year ago it was the general belief among Seminole operators that most wells in that district could not be successfully or economically pumped. Also the idea was prevalent at that time that the crookedness of the rotary holes would cause a large amount of mechanical trouble and the use of the air-gas lift would leave the wells depleted with sand conditions and fluid levels unfavorable for pumping. At that time it was predicted that wells would be abandoned when the economic flowing and swabbing period was reached. Contrary to these beliefs it has been demonstrated that wells can be profitably pumped to limits as low as 10 bbl. of oil per day where conditions are favorable.

The Seminole field, unusual in its rapid development, has served as an experimental laboratory for many oil field pumping devices with which this paper will not concern itself. Discussion will be confined to equipment and methods in general use throughout the field. The outstanding features of equipment and pumping operations covered in this paper may be summarized as follows:

1. Pumping equipment from the standpoint of prime movers, energy cost, power transmission equipment, derricks, counterbalances, beam hangers, tubing, sucker rods, pumps, etc.

2. Pumping problems peculiar to the Seminole field, including the proper time at which to change from air-gas lift flowing to pumping.

Pumping Equipment

There have been no basic changes in pumping equipment in the past 20 years with the exception of some refinements in design brought about by the demand for equipment suitable for pumping deep wells. Results of research in the heat treatment of metals and progress made by the American Petroleum Institute in standardization of equipment, together with the cooperation of oil field equipment manufacturers, have

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greatly aided in the development of the present-day deep well pumping equipment.

At best, the pumping of wells by means of a string of sucker rods operating a reciprocating pump on the end of tubing near the bottom of the well is an inefficient operation. The motive power must pass through many stages of transmission of low efficiency involving large energy losses. Not only is the power loss a factor deserving of attention but the constant replacement and repair of equipment comprising the whole standard beam well installation results in expensive downtime which may be reduced by more careful selection of equipment.

Prime Movers

Prime movers used on most Seminole pumping wells are gas engines ranging from 30 to 50 hp. Where electricity is used, the motor is either of 20/50 or 25/65 hp. rating. On Aug. 1, 1928, there was a total of 589 pumping wells in the Seminole field, of which 75 well, or 12.7 per cent., were using electricity for power. The remainder, or 514 wells, were equipped with gas engines, with a few exceptions where the steam drilling engine was still on the location pending delivery of the permanent engine or motor.

Steam engines are used as pumping power only temporarily, for the reason that equipping a lease for pumping with steam calls for a large investment in materials which have a rapid depreciation in value. In addition the cost of fuel necessary to generate steam to pump a Seminole well is estimated at $11.45 per well per day on the basis of 4 per cent. engine efficiency and gas at 25 c. per 1000 cu. ft. In a field where the conservation of fuel gas is necessary, the use of gas for generating steam for pumping is too expensive when an equal amount of power may be delivered by other types of prime movers at one-third the fuel cost.

It is estimated that 90 per cent. of the gas engines in use in the Seminole field, are rated by the manufacturers at 40 hp. However, if these engines were given an American Petroleum Institute horsepower rating it is probable that there would be disclosed a wide variance in power capacities because of the tendency among manufacturers to underrate their engines. Generally speaking, an engine capable of carrying three times the indicated pumping load at a reasonable speed is considered adaptable for oil field pumping and pulling.

An example of power requirement for pumping a typical well in the Bowlegs field, Seminole district (December, 1927), with a gas engine follows: Total depth, 4150 ft.; total depth to working barrel, 4124 ft.; size rods, $\frac{3}{4}$ in.; size tubing, $2\frac{1}{2}$ in. (external upset); size working barrel, $2\frac{1}{2}$ in. by 10 ft. (liner type); engine data, 40-hp. 2-cycle gas engine; daily fluid production, 100 bbl. oil; no water. The power tests were: Run No. 1, indicated horsepower, 20.5; No. 2, 25.9; No. 3, 28.2; No. 4, 26.8.

The indicated horsepower as shown by these tests was computed from continuous indicator cards which recorded the power strokes of the engine through complete pumping cycles of the well. The runs were made with varying types and weights of counterbalances operated at different speeds. It was found that the power requirements within limits vary as a function of the effective counterbalance as well as the load peculiarities of the well when operating at constant speeds.

When a pumping engine is used for pulling and running tubing and rods, it is often run at speeds in excess of that for which it was designed. Engines also are frequently given as much overload as they will stand and as a result bearings run hot, foundation bolts loosen, cylinder walls score, and pistons have been known to break. Actual power delivery under such conditions of field abuse is in excess of a rated safe load. With ordinary use the 40-hp. gas engine with normal load characteristics has given satisfaction.

While little conclusive evidence is available as to amount of formation gas per barrel of oil produced by Seminole wells, several surveys have been made in an effort to determine this factor. The wells have been shown to vary greatly in this regard due to different conditions as to fluid level, sand conditions, location in field, etc. In Table 1 results of some of these surveys are given, the figures being averages for groups of wells as shown.

Table 1.—*Production of Formation Gas per Bbl. Oil, Seminole Wells*

Field	Date	Number of Wells			Average Daily Oil Production, Bbl.	Formation Gas per Bbl., Cu. Ft.
		Pumping	Other Methods	Total		
Seminole City........	March, 1928	56	5	61	86.3	427
Bowlegs.............	March, 1928	8	2	10	116.2	373
Bowlegs.............	August, 1928	29		29	105.8	195
Little River..........	August, 1928	12		12	54.7	200
Weighted averages................		105	7	112	90.2	337

The gas-lift wells are less depleted and have a greater reserve of formation gas than the older pumping wells. A number of operators of gasoline plants in the Seminole district have found that the gas-oil ratio of pumping wells is increasing, and also the total volume of casing-head gas from some of the leases has materially increased, although the oil production of these leases has followed a normal decline. It is probable that the present supply of fuel gas in the Seminole field is adequate for the producing life of the field on a gas engine pumping basis.

Energy Costs

The cost of fuel for pumping a full-time Seminole well with a gas engine may be estimated either on the basis of the field purchase price of fuel gas or on the basis of the sales value of the return residue gas. Fuel for a gas engine operating at 15 per cent. efficiency on gas of 1000 B.t.u. at the field rate of 25 c. per 1000 cu. ft., costs $3.08 per day, while fuel cost based on the sale value of residue gas at 6 c. per 1000 cu. ft. is 74 c. per day.

Operators using electrical power can obtain rates as low as $0.012 per kw.-hr., depending on the demand and energy charges less the prompt payment discount and any load factor discount that may be credited. Energy requirements for a 4000-ft. well pumping 100 bbl. of oil per day powered by a 20/50-hp. motor ranges from 220 to 350 kw.-hr. per day. The wide range of power required may be caused by faulty counter-balancing, poor pumping motion, varying friction losses, and a pumping speed not suited to the best motor efficiency. Assuming an energy requirement of 285 kw.-hr. per day at an over-all rate of $0.012 per kw.-hr., the cost of electrical power would be $3.42 per well per day. A typical example of the cost of power for an electrical unit operating in the Seminole district is shown in Table 2.

Table 2.—*Cost of Power for Well in Earlsboro Field, April,* 1928

Total depth	4300 ft.
Total depth to working barrel	4267 ft.
Size of rods	¾ in.
Size of tubing	2 in.
Size of working barrel (liner type)	2 in. by 10 ft.
Motor	20/50 hp.
Daily oil production (no water)	80 bbl.
Daily power requirement	242 kw.-hr.
Power cost per day @ $0.012 per kw.-hr	$2.92

In a field where the natural gas supply is considered insufficient and the field rate for gas is too high for economic operation, a group of wells may be profitably produced by using electrical equipment. It is claimed that the electrical pumping installation is justified in view of the advantages of an evenly applied torque which reduces the impact loading on power transmission and well equipment. This factor is often considered to be of sufficient consequence to justify an additional power cost which may be incurred through use of electrical equipment. The final selection of a prime mover should not be made therefore until each phase of the power question has been investigated.

Power Transmission Equipment

The type of power transmission equipment is more or less controlled by the choice of prime mover and the operator must make his selection from a few types of clutches, belts and rig irons.

Standard reverse gear clutches may be purchased complete with the gas engine, or at an additional cost of about $260; the regular clutch may be replaced with a heavy duty roller-bearing clutch which is sturdier in construction. Because of the repair downtime of the regular clutches, there is some preference shown in the field for the heavy duty reverse gear clutch. The driving ratio from pulley to bandwheel based on a 16-in. pulley and a 11-ft. band wheel diameter is 8.25:1. For gas engines operating at 180 r.p.m. the well will pump about 22 strokes per minute.

Countershaft clutches with cross belt reverse drive are popular despite the fact that more belting is necessary and a larger engine house is required as compared to the standard reverse gear clutch installation. It is desirable when using the countershaft clutch to have an outboard bearing on the engine drive shaft so as to reduce the bending movement on the engine crank shaft and to reduce the thrust on the driving side of the engine bearing. Many operators believe that the countershaft clutches are less destructive to belting than other types of clutches, because of the large pulley diameter which decreases internal friction in the belt as well as providing more contact surface which decreases the belt slip. The standard Seminole type installation has a forward driving ratio of 8.43:1 and a reverse ratio of 5.5:1, but different ratios may be obtained by changing the pulley sizes to suit the best engine efficiency.

Electrical power transmission equipment manufactured at present conforms to the various types of either worm or herringbone reduction gears or a driving arrangement similar to the gas engine installation.

Belting has been given increasing attention in the past few years with the end in view of increasing belt service and, as a result, field practice is leaning toward wider and thinner belts. Many of the Seminole pumping wells have been equipped with a 12-in. 6 to 7-ply belt or the equivalent, but more recent replacements have been made with a 14-in. 6 to 7-ply belt. From the standpoint of the driving pulley, a 14-in. belt is preferable to a 12-in. belt because with equal conditions more horsepower can be transmitted to the bandwheel. With the wider belt the standard 11-feet bandwheel generally is built with a 14-in. face and any working of the jack posts or wearing of the bandwheel throws the belt slightly off and breaks the edge fibres to such an extent that a 14-in. belt may have only the strength and tractability of a 12-in. belt. This trouble can be eliminated by building up the bandwheel face an inch on either side and by rechecking alignment of the driven and driver pulley.

Belting requirements for a reverse belt countershaft clutch consists of a 10-in. 6-ply reverse cross belt, a 12 in. 6 or 7-ply forward driving belt and a 12 or 14-in. 6 or 7-ply belt from the clutch pulley to the bandwheel. It is customary to take off the reverse belt when the engine is doing straight pumping duty.

As a result of investigations conducted by the American Petroleum Institute improved types of belt, clamps and belt plate fasteners have been developed and adapted for oil field use. While most of the operators use an improved belt clamp, it is not unusual to find types of plate or butt end fasteners in regular service. As yet endless belt installations on Seminole beam wells are rare.

With the exception of some of the electrically equipped wells the average beam well at Seminole is equipped with a set of standard 6-in. rig irons of American Petroleum Institute dimensions throughout. The pumping stroke measured at the polish rod for various positions of the pin in the crank on standard 6-in. irons follows:

Crank Position	Length of Stroke, In.
First hole	24
Second hole	34
Third hole	44
Fourth hole	54

There are but few installations of special long-stroke pumping equipment in the Seminole field for the reason that there is not an excessive amount of fluid to be lifted in the average pumping well. It should be borne in mind that the universal application of air-gas lift to the Seminole field was responsible for a high early recovery of oil and for that reason the daily production of wells on the pump is small. It is estimated that the daily production from the average Seminole pumping well during the month of August, 1928, was 85 bbl. of oil and 30 bbl. of water per day. Long-stroke pumping equipment may be justified on wells of this size if it can be shown that the decrease in reverse loading on the rods is responsible for a substantial decrease in rod breakage.

All-steel walking beams and pitmans are in use to some extent but most of the operators use timber throughout. Some wells are equipped with an all-steel pitman, a brief description of which may be of interest. It is made from a 10-ft. length of second-hand 6⅝-in. casing. Extending down from the top of the pipe are welded two 3 by 5⁄16 by 32-in. steel reinforcing bars designed to withstand the shearing stress induced by the stirrup bolts. The pitman crank bearing is made by splitting the end of the pipe and working it out in the form of a housing in which is welded a babbitt-lined half section of pipe over which is a mated upper half bearing riding under a metal key.

Derricks

During the rush development of Seminole, 123-ft. rotary drilling derricks with 24-ft. base and of steel or turnbuckle design were used.

In production operation some operators have adopted the policy of leaving the rotary derrick over the completed well while others replace it with a steel pumping derrick, 84 by 20-ft. base, moving the drilling derrick to a new location.

Where the 123-ft. derrick is left over the well, much time can be saved in pulling rods and tubing. Following is a table which shows a comparison of the time required to pull rods and tubing with an 84-ft. pumping derrick and a 123-ft. drilling derrick:

	84-ft. Pumping Derrick	123-ft. Drilling Derrick
Number of joints per stand	2	3
Round trip with rods, hr	4	3
Round trip with rods and tubing, hr	18 to 20	12 to 15

Ordinarily rods are pulled in doubles in a pumping derrick and laid down on the walk, while with a drilling derrick rods are pulled in trebles and hung on a rod hanger inside the derrick. The latter method of handling accounts for the saving in time during pulling operations. The above figures are the result of a time study which reflects average conditions where no serious difficulties are experienced.

If the drilling derrick is to be replaced, the cost of the pumping derrick should be figured on the following basis: (1) cost of the pumping derrick, delivered, and erected on the location; (2) cost of dismantling and hauling the drilling derrick away; (3) depreciation of the drilling rig; (4) the additional expense in building smaller foundations or preparing the drilling derrick foundation for the pumping derrick; (5) the loss in deferred production while the derrick change is being made.

Operators following the practice of replacing the drilling derrick with a short pumping derrick estimate that it is economical on the basis the following features: (1) the drilling derrick is capable of drilling at least five deep wells; (2) the drilling derrick presents a wind hazard which should be avoided for the safety of workmen and lease equipment; (3) where a number of wells are being drilled in a district, it is claimed that there will be less money invested in derricks, if the completed wells are equipped with medium priced pumping derricks.

Counterbalances

While weighted bandwheel, crank, or pitman counterbalances are used on Seminole pumping wells to some extent, the most common installation is of the "grasshopper" or weighted walking beam type. The

preference shown for the latter type of counterbalance by no means condemns other kinds; instead, it reflects the tendency of field operators to pursue practices of long standing. It therefore appears that the relative usefulness and the mechanical advantages and disadvantages of counterbalances, as well as the theory of counterbalancing, merits more study than is usually given to this problem.

Bandwheel counterbalances are easily adapted for long-stroke pumping and may be operated at speeds at which heavy vertical lift counterbalances would be impractical. Among the disadvantages of the bandwheel counterbalance is the fact that it tends to throw the bandwheel out of alignment, loosen the jack posts, and induce excessive wear on the bandwheel bearings. Crank counterweights as used on the electric installations provide an opportunity for spacing the counterweight on the arc of rotation as well as with respect to the crank shaft. Pitman counterbalances give a combination effect of rotational and vertical lift motion which has desirable features, yet when the pitman must be taken off the crank for pulling the rods or tubing, the counterweights are cumbersome to handle.

Fig. 1 is a diagram of the grasshopper counterbalance which is in general use in the Seminole field. When properly weighted for deep well pumping, the pony beam or tailboard and the walking beam are often loaded beyond the safe working stress for wood. Pumping at a depth of 4500 ft. with an effective counterbalance weight of 9000 lb., unit fiber stresses in wood pony beams and walking beams may exceed 2000 and 1300 lb. per sq. in., respectively. This condition can be corrected by installing on top of the walking beam an inverted king post truss 2 ft. in height with a steel tension member having a cross-sectional area of 1.3 sq. in. The steel rod or cable should run from the well end of the walking beam to the end of the pony beam with the king post centrally located. Compared to an equal counterbalance weight hung from the walking beam, the grasshopper counterweight has a greater counterbalancing effect but the momentum of the weight resists reversal and as a result the pony beam hanger slackens at top of the stroke and must carry heavy impact loading at the bottom of the stroke. Counterweights hung from the walking beam do not have such rapid acceleration as the grasshopper counterweights, and for that reason a better balancing effect may be obtained at high pumping speeds by using the latter type.

As much as 20 per cent. power can be saved on a properly counterbalanced pumping well where the combination of the counterweight and well load requires an even torque. Under such conditions, rod breakage is decreased and the wear and tear on rig equipment is minimized. It therefore follows that wells should be counterbalanced so as to require equal power on the upstroke and downstroke.

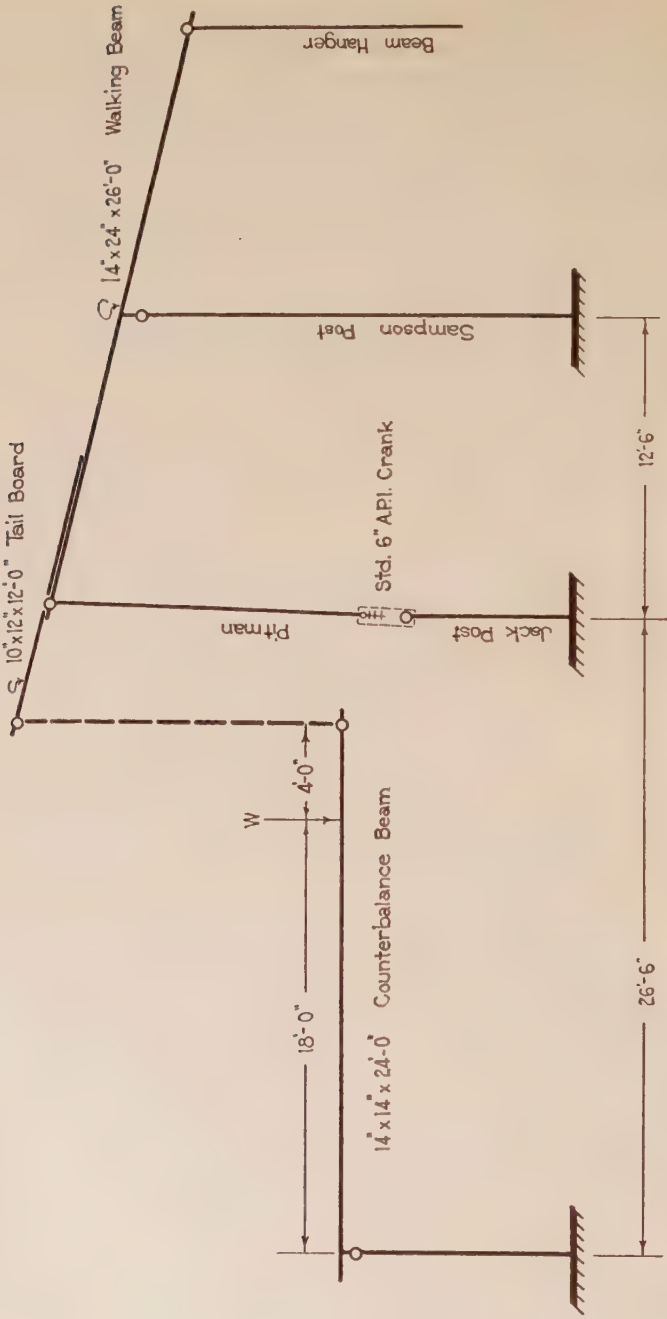

Fig. 1.—Grasshopper counterbalance.

The amount of effective theoretical counterbalance is equal to the weight of the beam hanger and the net weight of the rods (including rod guides, plunger, etc.) plus one-half the weight of the fluid on the pump plunger. The work done during a pumping cycle by prime movers on wells counterbalanced in this manner is the equivalent of raising one-half the weight of the fluid on the upstroke and to raising an equivalent amount of counterbalance weight on the downstroke.

Let W_e = effective counterbalance weight in pounds.

w_r = weight of rods less the weight of the displaced fluid plus the weight of beam hanger, rod guides, pump plunger, etc.

w_o = weight of fluid on the plunger in pounds.

A_p = area of the pump plunger less the area of the rods in square inches.

L = depth from the well head to working barrel in feet.

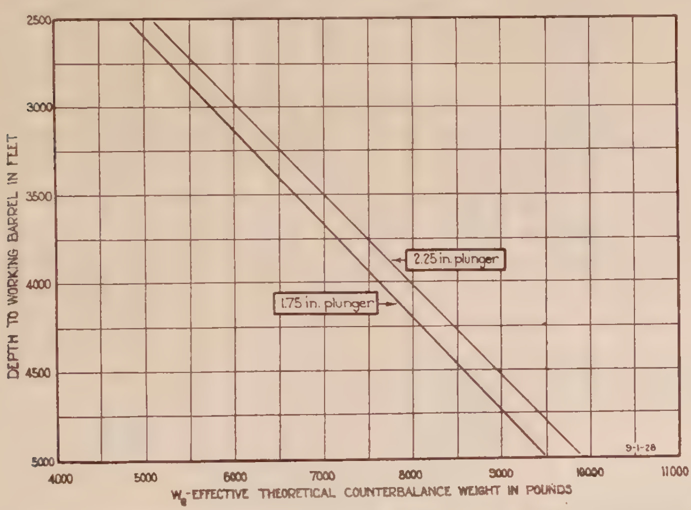

FIG. 2.—DEPTH-COUNTERBALANCE GRAPH FOR ¾-IN. RODS, 40° A. P. I. OIL, NOMINAL 2 AND 2.5-IN. PUMPS.

From the preceding paragraph the theoretical effective counterbalance may be expressed,

$$W_e = w_r + \frac{w_o}{2} \tag{1}$$

Assuming the following conditions:

Size rods, ¾ in. by 25 ft., pin end, 1.66 lb. per linear foot.

Production data, 40° A. P. I. gravity oil, 0.359 lb. per sq. in. per ft. of head and 6.85 lb. per gal. No water with the oil.

Weight of beam hanger, 200 lb.

Substituting the assumed values in formula 1 and reducing,

$W_e = 200 + L(1.503 + 0.18\ A_p)$

Fig. 2 shows the relationship between well depth and the theoretical effective counterbalance weight required under certain conditions. Values for the curves were computed from the above formula and adapted for wells using a plunger of 1.75 in. and 2.25 in. diameter for nominal 2-in. and 2.5-in. pumps, respectively. After reading the effective counterbalance weight from Fig. 2, the actual weight to be added to the counterbalance beam may be read from Fig. 3, provided that a grasshopper counterbalance, as shown by Fig. 1, is used. A practical method of

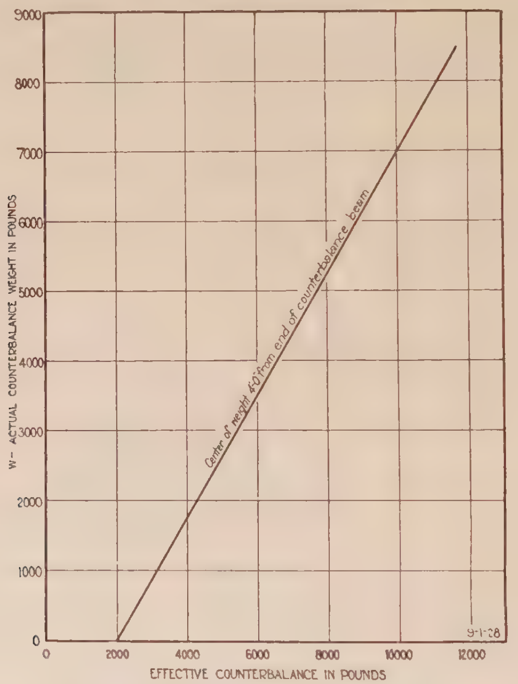

FIG. 3.—EFFECTIVE COUNTERBALANCE ADAPTED FOR FIG. 1 GRASSHOPPER TYPE.

arriving at the correct counterbalance weight is calculated from a dynamometer weight card showing the load through a complete pumping cycle.

Let M_u = mean weight in pounds during the upstroke.

M_d = mean weight[1] in pounds during the downstroke.

Then

$$W_e = \frac{M_u + M_d}{2} \tag{2}$$

BEAM HANGERS

Deep-well pumping calls for a pumping stroke of sufficient length to discount some of the effect of the stretch in the rods. With this in mind,

[1] By mean weight is meant the average weight ordinate rather than the arithmetical mean between maximum and minimum.

most operators in the Seminole field pump their wells in the third or fourth hole, which is equivalent to a 44 or 54-in. stroke at the polish rod. With the walking beam installed so as to rock an equal distance above and below the horizontal position, the lateral movement of a point at the end of the beam where the beam hanger rests is equivalent to about 3 in. If some type of straight-lift hanger is not used, the constant bending of the polish rod will soon fatigue the metal and result in a failure. To overcome this operators generally use some approved type of straight-lift hanger. These hangers either use the horsehead principle in connection with a cable or are designed to accomplish the same purpose by means of a jointed hanger which can approach a straight-line motion.

Tubing

The size of tubing used in Seminole pumping wells ranges from 2 to 4 in. in nominal diameters, depending on the daily fluid production of the well, size of rods used, method of pumping, and the judgment of the operator.

A number of wells now pumping had been producing on the air-gas lift with 2½-in. external upset seamless tubing and when put on the beam the same string of tubing was used. This accounts for a great many pumping wells using 2½-in. rather than 2-in. tubing.

For wells producing 200 bbl. of fluid per day or less it is practical to use 2-in. tubing if ¾-in. rods are used. When a tapered rod string made up of ⅞ and ¾-in. rods is used in the well, 2½-in. tubing is required to give clearance for the larger rods.

Tubing sizes of 3 and 4-in. are used on pumping wells when they are produced by a combination lift and pump method. The larger flow area is necessary to maintain a proper fluid velocity.

Tubing Collar Protectors

Many of the first wells put on the beam in the Seminole field showed immediate and excessive wear in the tubing collars. An outstanding example of this was a well which had 20 tubing collars replaced after the first 30 days' pumping. A collar for 2.5-in. external upset tubing, taken from the string at a point 525 ft. from bottom, measured only 3.36 in. outside diameter instead of its normal 3.66 in. This wear was sufficient to cause the threads to become visible on the outside of the collar. Only one side of the collars showed evidence of wear, indicating that the collar wear was a result of tubing movement while pumping rather than abrasive effect of running tubing in the hole.

Operators first used red swab rubbers as protectors for tubing collars in wells which caused excessive trouble. After a time the red rubber would begin to disintegrate and break off in small pieces. Protectors

were then made with rings of canvas belting, 1 to 1.5 in. in thickness, bolted on the tubing at the collar ends between two cast iron split clamps. This type of protector has given fair service, yet, after a short time in the well, the belt packing shreds and pulls out in strips, eventually dropping down the hole where it obstructs the pump valves and leaves the iron rings loose and ineffective on the tubing.

An apparent solution for the tubing collar protection problem is a 10-ply, cord rubber molded cylinder about 18 in. long and split down one side. The guide is forced over the collar and secured in place with two thin steel straps riveted on the cylinder near each end and fastened shut with a cotter pin. Specifications on this type guide may be changed to require a binding strap of noncorrosive metal instead of the steel strap.

The usual interval between tubing collar protectors varies from 3 to 5 joints and 20 to 30 protectors are generally required per well. Ordinarily, no protectors are used in the upper 2000 ft. of hole.

Rods

Since repair and replacement of sucker rods on a pumping well constitutes one of the chief sources of downtime and deferred production, rod string design and care of rods should have the attention of every operator. Most of the pumping wells in the Seminole field are equipped with a straight string of 3/4-in. by 25-ft. pin-end heat-treated rods. At the present time, most operators are buying the A. P. I. rods, which are desirable from the standpoint of interchangeability and which show a better service record in the field. To arrive at the proper idea of the desirability of a rod string, either straight or tapered, a study of the characteristics of the well in which the string is to be used should be made.

Fig. 4 shows the kind of rod breaks, whether body or pin break, and the depths at which the breaks occurred, relative to the number of days the rod string was in service on a well located in the Little River field, Seminole district. While this particular string of rods seems to have passed its economic limit of service before it was replaced, the record demonstrated the need of analyzing rod breakage on individual wells rather than relying upon general data covering average conditions. In other words, the true measure of analyzing rod breakage in view of decreasing the frequency of rod breaks in any one "breaking zone," is the study of the rod service in individual wells. From Fig. 4 it may be noted that 84.2 per cent. of the total number of rod breaks occurred in the first 1400 ft. below the surface. This would indicate that the upper part of the rod string is underdesigned, and that a taper string of about 1500 ft. of 7/8-in. rods, with the remainder of the string made up of 3/4-in. rods, would probably have given better service. This combination would be 33.8 per cent. stronger in the first 1500 ft. and would increase

the weight of the string 13 per cent. at about 48 per cent. increase in cost of the upper 1500 ft. While the cost shows a relatively high figure, a reduction of rod breaks of 20 per cent. would more than offset the increased cost of the combination string.

Other tapered string combinations used by some of the operators in the Seminole field are made up of about 2500 ft. of $\frac{3}{4}$-in. rods in the upper section and 1500 ft. of $\frac{5}{8}$-in. rods in the lower section, on the basis of a 4000-ft. string. This combination has an approximate weight of 5875 lb. and is about $7\frac{1}{2}$ per cent. lighter than a 4000-ft. straight string of $\frac{3}{4}$-in. rods. The ratio of the breaks in the $\frac{3}{4}$-in. rods as compared to the $\frac{5}{8}$-in. rods runs about 4 to 1, indicating that a string of balanced strength has not been made.

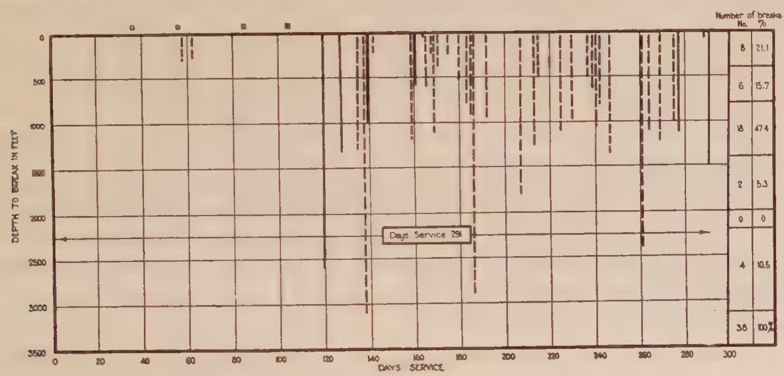

FIG. 4.—SUCKER-ROD BREAKAGE.

Legend: Body break— — — —; pin break ————; no information available ☐.
Well data: Size rods, $\frac{3}{4}$ in.; size tubing, $2\frac{1}{2}$ in.; stroke, 44 in.; total depth, 4209 ft.; pump, $2\frac{1}{2}$ in. by 10 ft.; speed, 21 strokes per min.; grasshopper counterbalance.

Figs. 5 and 6 illustrate that the serviceable life of the rod string is not entirely controlled by the number and frequency of breaks. The rods used in the wells which furnished data for these graphs were replaced because of fatigue of the metal together with many weakened places in the rod string, due to wear occasioned by rubbing on the tubing. This further demonstrates that the economic life of sucker rods used in pumping Seminole wells is so largely controlled by the characteristics of the particular well that generalizations on the frequency and location of rod breaks are of little value, and each well presents a problem in itself which should be corrected by proper counterbalancing and pumping speed, rod guides, smaller pump, or possibly a tapered rod string.

Tapered rod strings are not necessarily the cure for all rod troubles in the Seminole field as crooked holes and improper rod protection, as well as the practice of laying the rods down on the walk, may be the cause of rod-fishing jobs on wells that are correctly counterbalanced and running at a proper speed. Care in handling the rods during pulling opera-

tions is therefore of considerable importance as a slight kink is apt to cause a break under full pumping load.

Some operators in the Seminole field make a practice of keeping two strings of rods at each pumping well; one string is run in the well, and the

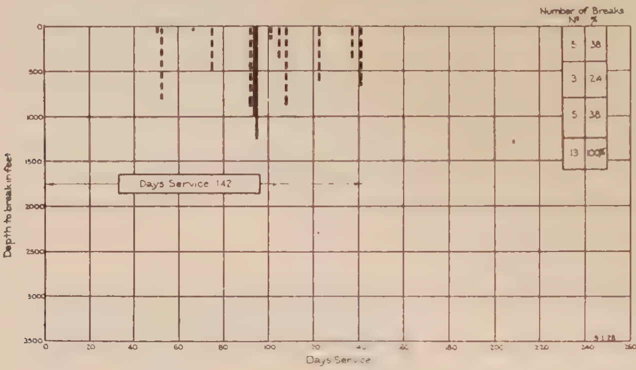

FIG. 5.—SUCKER-ROD BREAKAGE.

Legend: Body break — — — — ; pin break————.
Well data: Size rods, ¾ in.; size tubing, 2½ in.; stroke, 44 in.; total depth, 4130 ft.; pump, 2½ in. by 10 ft.; speed, 26 strokes per min.; grasshopper counterbalance.

other is allowed to lie out in the weather. It is thought that sucker rods which show evidence of metal fatigue will tend to return to their normal state when allowed to lie in the heat of the sun. However, it is improbable that this treatment produces the proper annealing on the rod because

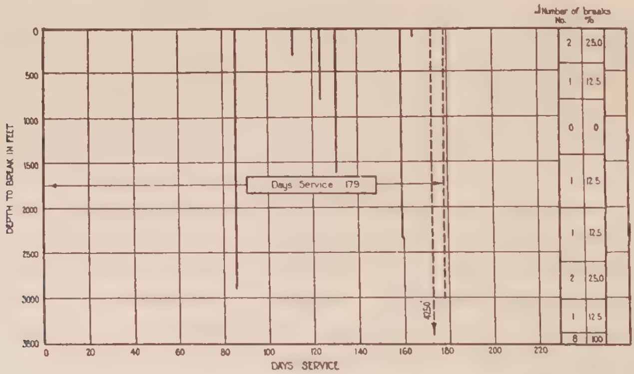

FIG. 6.—SUCKER-ROD BREAKAGE.

Legend: Body break— — — — ; pin break————.
Well data: Size rods, ¾ in.; size tubing, 2½ in.; stroke, 44 in.; total depth, 4323 ft.; pump, 2½ in. by 10 ft.; speed, 22 strokes per min.; grasshopper counterbalance.

the minute fractures or "slip planes" in the crystalline structure of the metal require a fusing temperature well over 1400° F. to reweld the minute crystalline flaws which are a result of operating the rods above the elastic limit of the metal.

Rod breaks occur in either the pin or the body of the rod in about the ratio of 4 to 6. The reason for pin breaks in A. P. I. ground shoulder rods may often be traced to the fact that dirt and grit have collected on the pin shoulder of the rod, making it impossible to buck the joint up flush to the shoulder, thereby losing the strength of the pin shoulder and throwing an enormous bending moment on the rod pin as the rods vibrate during the pumping motion. Body breaks on the pin-end heat-treated rods occur in the untreated section of the rod often 2 ft. from the pin. During the early development of heat-treated rods, it was common to have body breaks occur about 6 in. from the pin at the base of the heat treat, but this is no longer the rule. There are a few types where rods are heat-treated the entire length and are of course the exception to the usual cases of body breaks in rods which are heat-treated on the ends.

Because of the crookedness of the holes, there is a tendency of the rods to wear at the couplings and boxes as well as wear through the tubing. Most of the pumping wells require rod guides. Various types of rod guides have been on the market for some time, such as the wooden or bronze guides which clamp on at the body of the rods. However, during the last year or two, rod guides designed to go on the rod coupling have been perfected and are equipped to use either bronze or a composition jacket to serve as the protector. Crude oil that has poor lubricating qualities allows extraordinary wear on rod guides, sucker rods and tubing.

Pumps

Pumps of practically every type and design are in use in the Seminole field, depending upon the varying well conditions and the desire of operators to experiment with different types in order to arrive at a pump best suited to their individual operations. The general classification of pumps comprises the following types: Combination cup and plunger, liner, fluid-packed, and inserted barrel.

The common working barrel has its disadvantages in the Seminole field for the reason that the cups on the traveling valve must pass down through the tubing as the rods are run, and as a result, any burrs or abrasions on the inside of the tubing tend to score the cups, thereby reducing their efficiency before they enter the working barrel. A study of 15 installations of the common working barrel has shown that the cup trouble from this type of pump is practically twice the cup repair time on (liner) pumps which can be run in the well as a complete unit. While there are disadvantages in the use of the common barrel installation, one of the chief advantages is that the first cost of the common working barrel and traveling valve is considerably less than the first cost of the more complicated pumps, and if the operator makes a careful study of the performance of various types of pumps, wells can be found in which

the common type of pump will operate satisfactorily. Where the common type is installed, a 4 or 8-cup valve assembly is used.

The usual standard-liner type of pump as adapted for deep-well pumping is made up of a working barre jacket containing a fitted cast-iron liner in which is operated a ground steel-fitted plunger 60 in. or more in length. The plunger for this type of pump is machined to a tolerance 0.001 in., more or less, depending on the characteristics of the fluid at the bottom of the hole. Wells in the Seminole field have temperatures at the sand face ranging from 125° to 145° F., varying with the relative amounts of formation gas and water present, and, as a result, it is difficult to make the correct plunger replacement when varying temperatures cause the plunger to fit either too tight or too loose. The reason for this is that the cast-iron liner has a lower coefficient of expansion per degree of temperature than the steel plunger. It is generally known that an increasing amount of water in a well results in an increased temperature of the fluid at the pump and results in a tighter fit of the plunger. As most pumping wells show an increasing production of water, the problem of plunger replacement in liner type pumps is therefore of considerable importance. An advantage of this type of pump is that the plunger may be placed in the working barrel at the surface of the well and run in with the tubing, thereby reducing the hazard of scoring the plunger by running it down through the tubing on the end of the rods. Replacements can be made by pulling the plunger and standing valve complete, which saves a tubing job in case the standing valve is not holding or is sanded up.

There are types of liner barrels that employ the use of cups on the plunger for a seal and the entire liner shell, plunger and standing valve may be run in the well at the end of the rods and locked in place above the gas anchor. While any type of liner barrel has a higher first cost than the common working barrel, there are operators who believe their use is justified because of the accessibility of the working barrel.

While fluid-packed pumps are advantageous in one field, they may not prove to be satisfactory in another because the efficiency of the liquid seal is a function of the fluid being pumped. This type of pump is adapted for lower gravity oils. A disadvantage of the pump is that it necessarily has a smaller plunger area for a given size of pump. It is adaptable for pumping wells of relatively small capacity making considerable water.

The inserted barrel type of pump sacrifices some capacity by reducing the plunger area, but it is usually conceded that this is more than made up in the over-all efficiency of the pump, and since the average Seminole pumping well does not require a pump of high capacity, it is common practice among operators to use some types of the pumps other than the common working barrel and plunger type.

TABLE 3.—*Volumetric Efficiencies of Well Pumps, Seminole Field, Oklahoma*

Well	Top Sand, Ft.	Total Depth, Ft.	Size of Tubing, In.	Length of Mud Anchor	Perforated Nipple	Pump Suction above Sand, Ft.	Working Barrel		Pumping Stroke			Theoretical Fluid, Bbl.	Production, Bbl.	Gas Volume		Ratio Gas to Oil, Cu. Ft. per Bbl.	Percentage Volumetric Efficiency
							Liner Type	Indicated Diameter, In.	Hole in Crank, No.	Length, In.	Speed, Strokes per Min.			Casinghead, Cu. Ft.	Delivery through Tubing, Cu. Ft.		
a	4,127	4,139	2½	44 ft., 2 in.	2½ in. by 2 ft.	18	2½ in. by 10 ft.	2¼	4	54	24	644	150	11,200	3,400	97	23.3
b	4,063	4,130	2½	23 ft., 0 in.	2½ in. by 2 ft.	− 43	2½ in. by 10 ft.	2¼	3	44	26	675	410	16,700	9,000	63	60.8
c	4,043	4,060	2½	27 ft., 7 in.	2½ in. by 2 ft.	11	2½ in. by 10 ft.	2¼	4	54	24	644	325	4,400	2,800	22	50.4
d	4,085	4,111	2½	23 ft., 6 in.	2½ in. by 3 ft.	− 1	2½ in. by 10 ft.	2¼	4	54	24	644	235	3,720	4,720	36	36.5
e	4,048	4,100	2½	47 ft., 7 in.	2½ in. by 2 ft.	− 3	2½ in. by 10 ft.	2¼	3	44	22	572	280	106,000	7,000	404	49.0
f	4,326	4,410	2	40 ft., 2 in.	2 in. by 2 ft.	− 43	2 in. by 10 ft.	1¾	2	34	17	206	150	52,300	500	353	72.7
g	3,950	3,983	2½	34 ft., 10 in.	2½ in. by 2 ft.	2	2½ in. by 10 ft.	2¼	3	44	18	467	125	110,700	2,000	900	26.8
h	4,152	4,173	2	23 ft., 0 in.	2 in. by 2 ft.	− 3	2 in. by 8 ft.	1¾	2	34	18	218	70	11,200	860	173	32.1
i	3,984	4,173	2	24 ft., 5 in.	2 in. by 2 ft.	−164	2 in. by 9 ft.	1½	3	44	18	178	75	1,000	500	20	42.2

While the average Seminole pumping well does not have a high gas-oil ratio, there is still the problem of anchoring off the formation gas in order to prevent "gas lock" in the pump. Gas anchors of different sizes and design are used. A type that performs satisfactorily, when the pump is correctly spaced, is made of 1½-in. pipe 8 ft. long and is made up under the working barrel and a 2½-in. perforated nipple below the working barrel is about 2 ft. in length.

Many pumping wells have a combination gas anchor and sand trap set below the working barrel. This installation is used on wells that show an excess of "floating sand" with the oil. It is considered economy to keep the sand from coming into contact with the working surfaces of the pump, even at the cost of pulling the tubing at intervals to empty the sand trap. Although the Wilcox sand is not what might be termed a sharp sand, the grains are extremely hard and rounded, varying in size from fine, rounded and oblong shapes to large grains. The fine sand grains, suspended in the oil, are carried into the pump and, unless some mechanical means is provided to trap out the sand, it will cut cups, score working barrels and wear ball and seat valves, rods and tubing. A simple sand trap can be made of one or two joints of 4-in. pipe torch-welded at three or four points over a 2½-in. mud anchor with a bull plug on the end. In the mud anchor a number of ⅜-in. holes should be drilled at a 4-in. staggered pitch in a 2-ft. zone 4 or 5 ft. below the fluid intake at top of the 4-in. pipe. The space remaining below the perforations serves as a sand trap with a volume limited to the length of the anchor and the diameter of the trap which is limited by the size of the oil string. The anchor above described is designed for 6⅝-in. casing, but if the well is finished with 5$\frac{3}{16}$-in. casing the trap should be made of 3 and 2-in. tubing.

Volumetric efficiency of pumps varies within wide limits, but Table 3 reflects fairly high volumetric efficiency, taking into consideration that the stretch in the rods possibly accounts for as much as two-thirds of the loss in pump displacement over its theoretical capacity. The stretch in a 4000-ft. string of ¾-in. sucker rods pumping 38-gravity oil inside of 2-in. tubing is estimated to be about 20 in., based on the total load in pounds, supported by the traveling valve or plunger plus an allowance for friction. Heavy impact loads at high pumping speeds will increase the elongation of the rods as compared to a slow uniform motion resulting from proper counterbalancing. Table 3 shows the performance of pumping wells under various conditions.

Downtime of Pumping Wells

The repair and replacement of pumping equipment have for many years been accepted as a necessary evil, but modern operations call for greater producing efficiencies and economies requiring a knowledge of the

amount and cause of "downtime." After the cause has been allocated, the best method to reduce the amount of "downtime" can then be applied.

From the standpoint of continuous operation, the "downtime" of pumping wells at the present time is not of as much importance as it will be when the producing sand nears its productive limit and vacuum is applied. At that period, one hour of "downtime" may be the equivalent of 3 hr. of off-production because of the time required for oil to come in the hole after the reservoir pressure of the productive sand has been dissipated.

It is interesting to know that the average hours off-production per pumping well per month in the Seminole field, based on data covering five months' operation of 188 wells, was 60.3 hr. per well per month, or practically 2 hr. off per well per day. Assuming that 30 per cent. or 177 of the total pumping wells did not pump off, the total deferred production per day due to downtime would be 1254 bbl. of oil, based on 85 bbl. of oil per well per day as the production from the average Seminole pumping well.

In some cases, tubing used in gas-lift operation is used again when the well is put on the pump. In wells where the gas had been introduced into the well through the tubing, it has been noted that excessive valve and pump "downtime" results from the use of the same tubing for pumping. Inspection has revealed that a scale or residue having iron sulfide characteristics coats the interior of such tubing. Particles of this compound are scraped from the tubing as the rods are run in and during pumping operations more of the scale is dislodged through softening effect of the oil together with the whipping of the rods. As a result, pump valves and standing valves become clogged with this material, obstructing the passage of oil. It has been suggested that this condition might be remedied by cleaning the tubing before running it in the well, either by means of an air-driven scale hammer or by an acid treatment.

The study of "downtime" continues to increase in importance as the well nears its economic producing limit, where an excess in equipment repair hastens the time of abandonment, resulting in a wasteful operation. Fig. 7 shows the percentage of "downtime" distributed by causes based on information from 30 per cent. of the total number of pumping wells in the Seminole field. It may be noted that 72 per cent. of the "downtime" is chargeable to subsurface equipment, while only 16 per cent. can be directly charged against surface equipment. The remaining 12 per cent. is made up of miscellaneous causes which are beyond the control of the operator.

Each item making up the "downtime" study covers a number of different makes and types of equipment. It is by means of such records that the equipment service of any group of pumping wells can be studied with the view of making a selection of equipment that is best suited for

the particular well. It would appear that tubing, rods, pumps and cups or plungers should be developed to a state of durability comparable with other pumping equipment, or that the present method of pumping oil wells is at fault and the field is open for someone to develop a pumping device which will displace the equipment now causing the most "downtime."

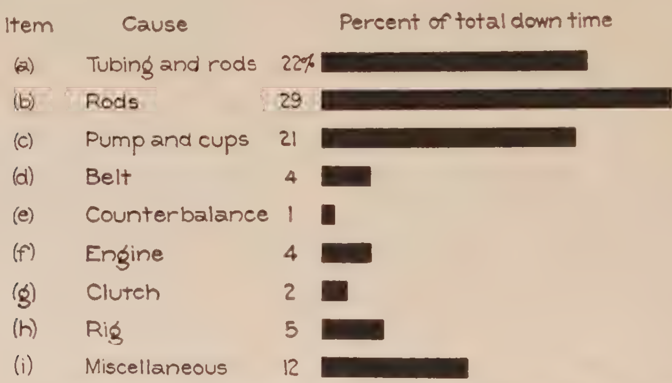

Fig. 7.—Downtime of pumping wells, Seminole field, Oklahoma (188 wells).
(*a*) Covers split tubing, sanded-up wells, tubing collar replacements, etc.
(*b*) Rod breaks and rods unscrewed.
(*c*) Standing valve, pump plunger, cups, or barrel.
(*d*) Belt breaks and belt tightening.
(*e*) Counterbalance.
(*f*) Engine and ignition.
(*g*) Clutch repair.
(*h*) Surface equipment not already covered.
(*i*) Miscellaneous, fuel or power, high water, fire, storms, waiting on crew.

Change from Air-gas Lift to Pump

The status of the average Seminole pumping well is that of a stripper which is being pumped as a last resort, after low fluid levels and water intrusion have made production by the air-gas lift method impractical.

Fluid levels in wells of Seminole City, the discovery field, have declined from about 600 ft., above bottom, in September, 1927, to about 100 ft. in September, 1928, while fluid levels of 300 ft. or more are common at the present time in the Bowlegs field which is 6 miles south and drilled in 9 months later than Seminole City field. The shut-in pressure above the fluid in some of the new wells in the south extension of the Little River field, ranges from 75 to 150 lb. per sq. in. where fluid levels raised to within 200 ft. of the surface. While accurate data, in regard to the fluid levels of producing wells in each field to date, are not available, the fluid levels of producing wells during cleaning-out operations or tubing jobs indicate that the true "reservoir pressure" has declined rapidly.

It is difficult to flow a well on lift by ordinary methods when it has a low gas-oil ratio and a static fluid level of less than 250 ft. When a

well is produced by air-gas lift, the differential between the working pressure and the reservoir pressure approaches zero for a flowing limit. Generally speaking, sometime before the flowing differential has reached a point where flowing requires excessive volume of air or gas, the well is in a condition bordering upon the limit of successful and economic lift operation. At this stage, it may be best to change the well over to pumping even though it produces no water with its oil.

Field reports show that at least 493, or 41.7 per cent., of the 1187 wells in the five large fields of Seminole district are making water and that many of the edge leases show the water production to have doubled during the last 3 months. The presence of water in edge wells has generally

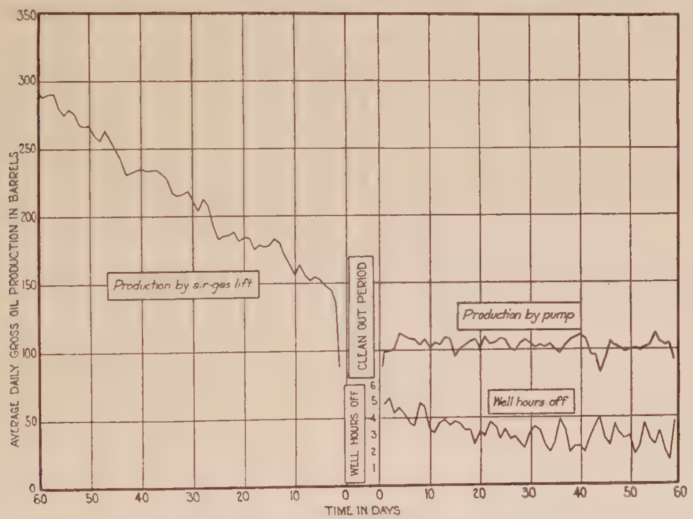

FIG. 8.—AVERAGE DAILY OIL PRODUCTION OF 46 WELLS LAST 60 DAYS ON AIR-GAS LIFT AND FIRST 60 DAYS ON PUMP, SEMINOLE FIELD, OKLAHOMA.

been the result of slow water encroachment, although scattering wells in all of the fields in the Seminole district showed water when first completed, even though some of these wells were thought to be higher structurally than their offset wells that showed no water. Because of corrosion caused by water in air-lift wells, it is usually desirable to change to the pump when the well starts making water unless gas is available for lift purposes. Even where gas may be used for flowing wells that are making water, a critical percentage of water production may give rise to heavy emulsions which can not be economically separated. On the other hand, if the same wells were put on the pump it is possible that the emulsion could be reduced.

Another factor in influencing the decision to change the producing method from air-gas lift to pump is the amount of daily well production. Opinion of Seminole operators vary in this regard, and minimum lift-

producing limits, ranging from 250 down to 50 bbl. per day, are not uncommon. Fig. 8 shows the average daily production from 46 wells in the Seminole field for periods of 60 days before and 60 days after the wells had been changed from air-gas lift flowing to pumping. The total well hours of trouble or "downtime" is plotted for the pumping side of the graph, but "downtime" is omitted from the air-gas lift side of the curve because lift operation is practically continuous with negligible "downtime." The last 24-hr. production on lift, as shown, averages about 135 bbl. per well. However, wells as small as 50 bbl., producing during the flush period of the field could be economically flowed by lift, while wells of similar production in the older fields would be difficult to flow at present because of water and low fluid levels. The productive capacity of a well, therefore, is not the true index as to the proper time at which to change from lift to pump and no arbitrary well production should be set as a minimum flowing limit.

Further reference is made to Fig. 8, calling attention to the characteristics of the lift wells after having been changed to the pump. While the production decline by lift appears to be rapid as compared to production decline by pump, the following factors should be considered:

1. Depending upon the efficiency of the pump, it has been demonstrated in some instances that daily production by pumping can be made to show an increase over daily production by the lift, where the lift is utilized to its practical flowing limit, probably because the reduction of "flowing head" on the producing sand increases the effective reservoir pressure and allows more oil to come in the hole when pumping is resorted to.

2. The oil production of some of the lift wells had a rapid decline following the first entrance of water. The flattening of the curve during the early pumping stage as compared to the later life of the flowing stage, in many of these wells, resulted from a more constant ratio of oil to water.

3. An average of 7 days' clean-out time between the change from lift to pump is responsible for an amount of "deferred" production which helps sustain the pumping curve.

4. The production by pump is further assisted by the results of cleaning out when the well is taken off the lift.

5. The change from lift to pump has taken place during the "flattening" of the production curve or that period in the life of a well when fluid levels have more or less stabilized as to hydrostatic head. For that reason, the pumping part of the curve should decline at a slower rate than the lift curve.

It is generally accepted as a fact that oil from a well that had been on lift tends to increase in gravity after the well has been put on the pump. When air or gas passes through a body of oil, it is to be expected that the

oil undergoes changes in gravity, volume and chemical constituents and that it will be stripped of some of its lighter ends.[2]

While field experimental data are limited, an investigation made on 13 wells showed the gravity to increase an average of 0.8° after the wells had been changed from lift to pump.

The average daily oil production of the 46 wells, as shown by Fig. 8, for the first 10 days on the pump is 102 bbl. per day or a decline in daily production, from the lift, of 33 bbl. Much of the "off"-production can be accounted for in the repair "downtime" of the pumping well. For

TABLE. 4.—*Number of Wells and Producing Methods in Seminole District*

Pool	Pump	Lift	Natural Flow	Swab	Off	Total Wells
Aug. 4, 1927						
Little River	0	0	1	0	0	1
Bowlegs	2	129	6	29	20	186
Seminole City	75	150	12	29	45	311
Searight	8	15	18	0	1	42
Earlsboro	11	16	61	12	34	134
Totals	96	310	98	70	100	674
Totals, per cent	14.2	46.0	14.5	10.4	14.9	100
Feb. 1, 1928						
Little River	19	57	4	5	12	97
Bowlegs	45	210	3	21	27	306
Seminole City	165	90	7	18	39	319
Searight	15	25	21	3	7	71
Earlsboro	73	129	20	31	38	291
Totals	317	511	55	78	123	1084
Totals, per cent	29.3	47.1	5.1	7.2	11.3	100
Sept. 5, 1928						
Little River	47	113	15	27	13	215
Bowlegs	173	110	0	11	33	327
Earlsboro	145	68	21	27	20	281
Seminole City	225	46	3	5	11	290
Searight	32	20	12	1	4	69
Totals	623	357	52	71	84	1187
Totals, per cent	52.5	30.1	4.4	6.0	7.0	100

[2] R. V. Mills, J. Chalmers and J. S. Desmond: A. I. M. E. *Tech. Pub.* 144 (1929) 15–17.

the first 2 months' pumping, this figure averages 3.29 hr. per well per day, which amounts to $6.58 per day estimated at the rate of 50 c. per man hour, on the basis of four men per hour, which is a conservative figure. The downtime, as shown by Fig. 8, shows a tendency to decrease near the end of the first 2 months on the beam.

In view of the operating difficulties connected with pumping, it is surprising that there has been such a rapid change from lift to pump methods. With lift equipment installed on the lease at a cost of $35,000 per well on the basis of 200 compressor horsepower and inclusive of pressure and gathering lines, it is no small matter to disregard that investment and add $3300 more to equip the well for pumping when the lift plant will either be shut down or operated at part load capacity.

Table 4 shows the status of the producing wells in the Seminole district as of Aug. 4, 1927, Feb. 1, 1928, and Sept. 5, 1928. A study of the table shows that the number of pumping wells is rapidly increasing and that the number of gas-lift wells is rapidly decreasing. In another year it is probable that very few of the wells now producing will be operated by a gas-lift. Some of the machinery installed for gas-lift operations will probably be used for injection or pressure restoration purposes.

It is interesting to note that on Sept. 5, 1928, 52.5 per cent. of all of the producing wells in the Seminole district were on the pump. These wells, however, only produced 15 per cent. of the total oil production of the district.

Acknowledgments

The writers wish to acknowledge the suggestions and assistance furnished by D. B. Dow, F. A. Lichtenheld, H. B. Thompson and C. E. Wright in the preparation of this paper.

Deep-well Pumping in California

By Hallan N. Marsh,* Los Angeles, Calif.

(Tulsa Meeting, October, 1928)

The subject of this paper is apt to bring to mind wells ranging from 6000 to over 8000 ft. in depth. However, it is uncommon to pump wells at depths greater than about 5000 ft. Fig. 1 shows the number of wells being pumped at various depths by one company in Southern California.

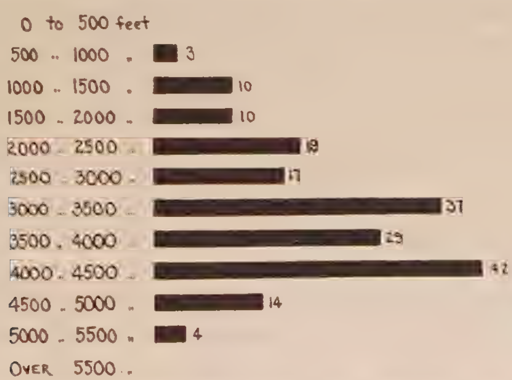

Fig. 1.—Number of wells being pumped by one company from various depths in Southern California.

A few companies have a very few wells pumping at depths greater than this. This paper will deal with wells between 3000 and 5500 ft. in depth. Most California oils at these depths are between 25° and 35° gravity. The subject is so broad that it will be necessary to omit many interesting phases, and to treat others very briefly. Power, power transmission equipment, power efficiency, counterbalancing, sucker rods, pumps and volumetric efficiency will be discussed.

Power

As a source of power, the 50/20-hp. electric motor is generally preferred. Input is generally between 10 and 25 hp. Due to the unevenness of the load, an input of 20 hp. on the low range is generally about all that these motors will carry without overheating, in spite of their overload capacity. In some cases the capacity of the motor limits the speed

* General Petroleum Corpn. of California.

at which a well can be pumped. Where an operator has a number of wells in a group, and maintains his own transformers and distributing lines, the power rate averages in the neighborhood of 1 c. per kw.-hr. This makes 1 hp. cost $0.18 per day, $5.37 per month, or $65.53 per year. Energy for a motor requiring 15 hp. input therefore costs $2.68 per day. In some localities, with large numbers of wells on one meter, the rate may go as low as six-tenths of a cent per kilowatt hour.

Gas engines still have a field of usefulness, and are preferred by a few operators. They should be of at least 40 hp. rating. Where electric power rates are high and gas is cheap there is a power cost saving in favor of engines that may more than offset their higher maintenance. Comparisons between the costs of maintaining engines and motors are apt to be misleading because most motor installations are modern, and the majority of engine installations are more or less antiquated. Hit-or-miss governors produce an uneven motion that is certainly deleterious to belts and rods, but engines with throttling governors are practically as smooth in operation as motors. The newer engines are superior in other respects to those made 10 or 20 years ago.

Steam engines are very little used except for temporary purposes. Where electric power is expensive, and boilers must be operated anyway for other purposes, they may be the most economical source of power, and are sometimes used.

Table 1 compares the cost of power generated by motors, gas engines and steam engines, subject to the assumptions noted.

Table 1.—*Costs of Brake Horsepower*

Cost of electricity per kw.-hr.	0.75 c.	1.00 c.	1.50 c.	2.00 c.	3.00 c.
Electricity for motor per month (assumed efficiency 85 per cent.)	$4.75	$6.33	$9.50	$12.66	$19.00
Cost of gas per M cu. ft. (assumed heat value 1000 B.t.u. per cu. ft.)	5 c.	8 c.	10 c.	15 c.	35 c.
Gas for gas engine per month (assumed efficiency 15 per cent.)	$0.61	$0.98	$1.12	$1.84	$4.29
Gas for boiler and steam engine per month (assumed efficiency 4 per cent.)	2.29	3.67	4.58	6.87	16.03

Power Transmission

Power is usually transmitted to the rods through the so-called standard rig, comprising belts, countershaft, bandwheel, crank, pitman and walking beam. The motor belt is usually 6-ply rubber, 10 in. wide, and the main belt of 6-ply rubber 12 in. wide. Many new rigs are being equipped with 12-in. motor belts and 14-in. main belts, which are expected to give more than proportionately better service. Bandwheels may be

either wood or steel and are now mostly 10 ft. dia., but new rigs are being equipped with 12-ft. wheels. The latter reduce the belt tension required, and provide a greater radius for bandwheel type counterbalances.

Rig irons are of nominal 6-in. size. Many of the old-fashioned wooden pitmans with babbitt and wooden block bearings are still in use, but are being gradually superseded by steel pitmans with adjustable bearings. Walking beams are mostly of wood, carried on babbitt bearings. They are not entirely satisfactory due to warping, and will probably be superseded by steel beams. This change has been delayed because some of the steel beams sold have not been of adequate strength. The total rod load is often as great as 14,000 lb., and may be even higher. This causes a bending moment in the beam of 2,000,000 in.-lb. or more. Babbitt bearings have to be replaced frequently. It is believed that the unit pressure is such as to cause an actual flow of the babbitt. The use of bronze inserts is proving a simple and satisfactory solution of this difficulty.

Double strap or cable pump adjusters with a set screw type of grip are in use. With strokes greater than 32 in., some sort of a straight line mechanism is very desirable to minimize bending of polish rods and wear of stuffing boxes. The so-called "mulehead," comprising a pair of arc-shaped channels over which cables pull, is perhaps most generally used. It is satisfactory except that the cable wears out rapidly. It can be shown geometrically that when the pivot point from which the rods hang is on top of the beam, its horizontal component of motion is 10 in. with a 40-in. stroke, whereas if the pivot point is lowered to a point on a level with the center bearing (with the beam at its midstroke) the horizontal component of its motion is only 1.3 in. Several hangers based on this idea are in use. Rod grips involving a toggle joint or lever action are coming into use. Aside from being easier to use they obviate the bending of polish rod that sometimes occurs in tightening up the set screw type of grip.

Single reduction units are now quite often used in connection with motors, taking the place of the motor belt and countershaft. Most of these are gears of spur, helical or herringbone type, but there are also chain drive and vee belt units. Some of the earlier reduction gears were unsatisfactory, due in part to the manufacturers not being familiar with the great overload capacity and underrating of oil field motors, but there are now available units that are very satisfactory in operation.

Some operators are driving their bandwheels by chain instead of belt, and are apparently satisfied with the change.

Double reduction gears (or the equivalent worm gear) are being tried out on a limited scale by a few operators, and give promise of being a great improvement. The elimination of both belts, countershaft, bandwheel, bandwheel shaft and crank, is much to be desired as these parts are a great

source of trouble. As soon as operators become thoroughly convinced that these reduction units are of adequate strength and durability, they will undoubtedly come into common use. A complete rig with double reduction gear costs about the same or a little less than a standard rig.

Power Efficiency

By measuring the electrical input to the motor with a watt-hour meter and the power delivered to the rods with a dynamometer, the over-all above ground efficiency can be easily determined. This efficiency varies in different instances from 15 to 65 per cent., depending upon the load

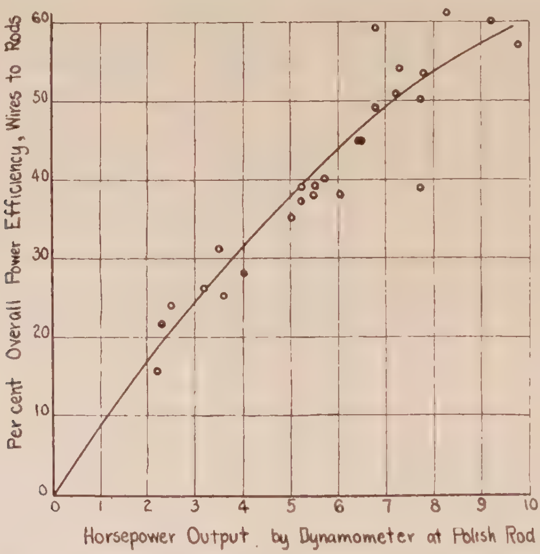

Fig. 2.—Efficiency of standard rigs for one group of wells as affected by load.

on the rig, the counterbalancing, and the condition of the rig as regards belt tension, alignment and lubrication. Power losses in a rig do not increase in proportion to the power throughput, so that higher loads generally result in higher efficiencies, as shown in Fig. 2. Note that these are over-all efficiencies, including motor losses, and that efficiency of rig alone would be higher.

Counterbalancing

During the upstroke of the rods, energy equal to the mean effective force on the upstroke times the length of stroke must be supplied to the rods. The rods in falling, return to the rig energy equal to the mean effective force on the downstroke times the length of stroke. The power

required at the rods therefore fluctuates from positive to negative and back on each pump cycle. Unless a counterbalance is provided, power and power transmitting equipment adequate to supply the maximum demand on the upstroke must be provided. This is impractical and uneconomical on deep wells. The following actual case illustrates this. A certain well has a maximum rod tension of 14,200 lb., a minimum rod tension of 4700 lb., and a mean tension of 9000 lb. By mean force is meant the mean force as determined from a dynamometer card by planimeter, and not merely the average of maximum and minimum tensions. If no counterbalance is provided, the rig and motor must be adequate to provide the maximum lift of 14,200 lb., but with a counterbalancing force of 9000 lb. provided, the rig need only supply a net force of 5200 pounds.

The theoretically correct amount of counterbalance can be easily calculated. Assume the load during the upstroke to be the net weight of the rods when submerged in oil, plus the force of the fluid on the total plunger area (not deducting for rod area). The weight on the downstroke is the net weight of rods when submerged in oil (oil is standing on the standing valve). The theoretically correct counterbalance is the mean between these calculated weights for upstroke and downstroke. This has been computed for the common sizes of pump and various oil gravities, and is shown in Table 2. Note that for the common 2½-in. pump and the middle range of gravities, the figure is approximately 2.2 lb. per ft. of depth.

TABLE 2.—*Theoretically Ideal Counterbalance (Lb. Per Ft. Depth; with ¾-in. Sucker Rods)*

Gravity of Fluid, Deg. Bé.	Nominal Pump Size		
	2 In.	2½ In.	3 In.
10	1.94	2.28	2.71
12	1.94	2.27	2.69
14	1.93	2.27	2.67
16	1.93	2.25	2.66
18	1.92	2.25	2.65
20	1.92	2.24	2.64
22	1.92	2.23	2.62
24	1.91	2.22	2.61
26	1.91	2.21	2.60
28	1.90	2.21	2.58
30	1.90	2.20	2.57
32	1.90	2.19	2.56
34	1.89	2.18	2.55
36	1.89	2.18	2.54

It is of value to know how reliable this theoretical figure is, and for that reason it has been compared with the correct figure as determined by dynamometer, for 10 wells picked at random. Ratios of correct counterbalance to theoretical counterbalance for these cases are as follows: 100 per cent., 98 per cent., 93 per cent., 99 per cent., 96 per cent., 93 per cent., 116 per cent., 97 per cent., 94 per cent., 93 per cent.; average, 98 per cent. Where the correct counterbalance is greater than the theoretical, it may be supposed that friction is greater on the upstroke than on the downstroke. Where less is required than calculated, it may be attributed to the lightening effect of gas in the tubing or to pump submergence.

There are several forms of counterbalance in use. Most common of these is the well-known concrete block hanging from the walking beam, and guided either by a lever or by sliding on pipes. If hung from the beam between the pitman and Samson posts, the effectiveness of the weight is of course reduced by the ratio of the distance from center bearing to counterweight line divided by the distance from center bearing to well line. If hung from a pony beam extending out beyond the pitman, the effective force is greater than the dead weight, but the travel of the weight is so increased that acceleration is excessive, causing the suspension cable to go slack at the top of the stroke, and the force to be so great at the bottom of the stroke that it is hard to make a pony beam strong enough to carry it. These arrangements are therefore not satisfactory for heavy wells with a fast stroke.

So-called bandwheel counterbalances are in general use, comprising weights attached eccentrically to the bandwheel, with means for releasing or centralizing them while pulling the well. The effectiveness of such weights is dependent upon the length of crank stroke used, and the bandwheel diameter. With short strokes they are very efficient, and with 12-ft. bandwheels they are satisfactory even for the longer strokes. The chief objection to these balances is that they put an undue load on bandwheel, shaft and crank pin, sometimes resulting in the failure of these parts.

Several different counterbalances have been built and tried which lift up directly on the polish rod or the well end of the walking beam. These have been of the weighted lever, helical spring and pneumatic types. They are all inherently unsatisfactory, because, as previously pointed out, the correct amount of counterbalance is the mean between the force on the upstroke and the force on the downstroke, and if the effectiveness of a counterbalance in this position is made greater than the force on the downstroke, the rods will tend to lift off from the beam, or the beam will tend to lift up on the Samson post. In practice, these counterbalances can not have more than about 50 per cent. of the desired effect.

A counterbalance pitman is coming into use comprising a steel pitman to which is permanently attached a shelf on which cast iron slabs may be stacked. This arrangement has obvious advantages. The chief objection seems to be that there is no advantageous leverage ratio, so that the dead weight must equal the effective weight, which should often be 10,000 lb. or more. This results not only in high first cost, but in difficult handling.

Counterbalance cranks are in use on several of the double reduction gears, and are also being tried on standard rigs. Some of them are very inadequate in amount, but a counterbalance of this type can certainly be made adequate on special units, and perhaps also on the standard rig. They may prove to be the best solution of the problem.

Counterbalancing merits this relatively long discussion, because it is a problem not yet satisfactorily solved, and one whose solution is essential to the efficient operation of a pumping rig. Pumping of deep wells without some counterbalance is almost impossible, and changing from a slightly inadequate counterbalance to one of correct amount has been shown by repeated tests to result in power savings of 10 to 20 per cent.

Sucker Rods

Transmitting power from the walking beam down through a mile of crooked hole is quite a problem. This is commonly done with steel sucker rods, but the dissatisfaction with this method is attested by the many attempts at radically different methods, hydraulic, pneumatic and electric. While these methods have attractive features, it may be noted that in spite of numerous trials, all of them remain decidedly in the experimental stage. (Gas-lift which is very successful in certain circumstances, is not included in the above category, and will not be discussed in this paper.) Sucker rods are commonly of ¾-in. size of the double pin and box type. Rods made to A. P. I. specifications are already coming into use, and are decidedly superior to previous types.

Fig. 3 shows frequency of rod failures as a function of depth to pump. The increasing trouble at greater depths suggests that at still greater depths stronger rods will have to be used. The use of larger rods is to be avoided because their greater weight augments the already serious problem of counterbalancing. The solution will probably be in the use of alloy steel rods, or the heat-treating of carbon steel rods.

Fig. 4 shows the depths at which breaks occur. The preponderance of breaks near the surface suggests that larger rods should be used for the top third of the string, and this has been tried with good results as regards elimination of failures. The increased frequency of failure at the very bottom of the string is undoubtedly due to buckling, caused by tight-fitting pumps and to the fact that the ordinay pump is partly double-acting. The increased frequency at about 70 per cent. of the depth is difficult to explain.

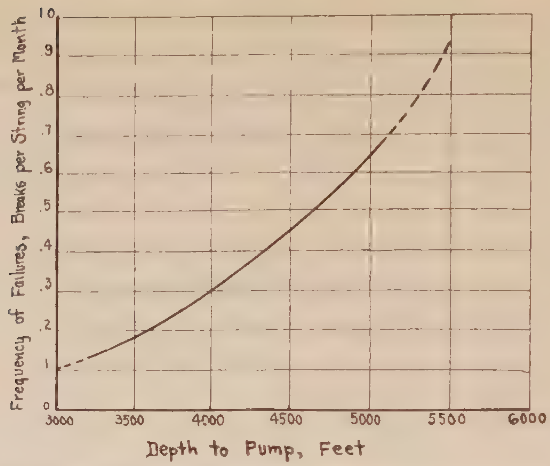

FIG. 3.—EFFECT OF DEPTH TO PUMP ON FREQUENCY OF SUCKER-ROD FAILURES (PUMPS MOSTLY $2\frac{1}{2}$ IN.; RODS, $\frac{3}{4}$ IN.).

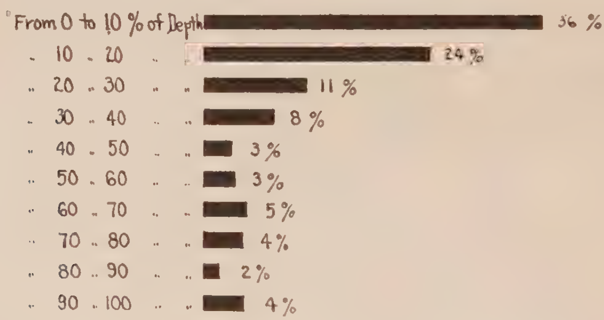

FIG. 4.—PERCENTAGE OF DEPTH TO PUMP AT WHICH SUCKER RODS FAIL.

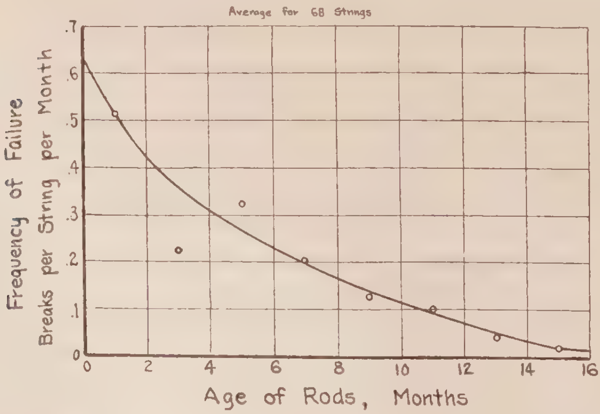

FIG. 5.—EFFECT OF AGE OF SUCKER RODS ON FREQUENCY OF FAILURE.

Fig. 5 shows the frequency of break as a function of the age of the rod. It is surprising that frequency of failure decreases with age. This is the opposite of what might be expected on the assumption that failures are due to fatigue. It must be concluded that there are weak rods in every string and that as these get weeded out, failures become less frequent. Classification of failures between body of rod, pin and coupling varies greatly between different makes of rods, but the average experience of one user, previous to the introduction of the A. P. I. pin is as follows: Body breaks, 48 per cent.; pin breaks, 49 per cent.; box breaks, 3 per cent. With A. P. I. specification rods, pin breaks are much less frequent.

The load to which rods are subjected is dependent not only upon the depth to pump, size of pump, gravity of fluid, and friction, but also on the motion imparted to the rods. As a basis of calculation it may be assumed that rods move with simple harmonic motion. If this were the case, the acceleration would be

$$A = \frac{S \times N^2}{705}$$

where A = acceleration in percentage of gravity.
S = length of stroke in inches.
N = number of lifting strokes per minute.

From this it can be seen that the acceleration varies as the length of stroke, and as the square of the number of strokes per minute. For a given rod speed, the acceleration is inversely proportional to the length of stroke. This indicates the advantage of a long stroke, but unfortunately the length of stroke (with standard rig) is limited by other considerations. As a typical case, let us consider a well pumping at 25 strokes per min. with a 40-in. stroke. From the formula, the acceleration is 35 per cent. gravity, which means that the tension due to the dead weight of rods and fluid would be increased 35 per cent. if the whole load were given this acceleration. Fortunately, the rods and fluid have some elasticity so that the whole string of rods and column of oil is not accelerated as fast as the polish rod.

Use of an accelerometer attached to the polish rod has shown that the actual maximum acceleration is always greater than the calculated acceleration, by a factor that averages around 1.80 and depends upon degree of counterbalancing, length of stroke and other variables. This apparent discrepancy is due partly to the fact that the pitman is not infinitely long, as it would have to be to give a simple harmonic motion, and also to the fact that the angular velocity of the crank varies from one part of the revolution to another.

Fig. 6 shows the angular velocity of the crank as a function of time for two wells, one of which was driven by an electric motor and had a nearly adequate bandwheel counterbalance, and the other was driven by a

steam engine and had no counterbalance. It is apparent that there was much more variation of angular velocity in the second case, but even in the first case this variation was considerable. When the calculated acceleration is corrected for the finite length of the pitman, and the variation of the crank velocity, it agrees satisfactorily with that measured by the accelerometer.

These curves are plotted from moving picture data. A graduated disk is set up in front of the crank, and a pointer is attached to the crank pin so that it moves over the disk. Moving pictures are taken of this

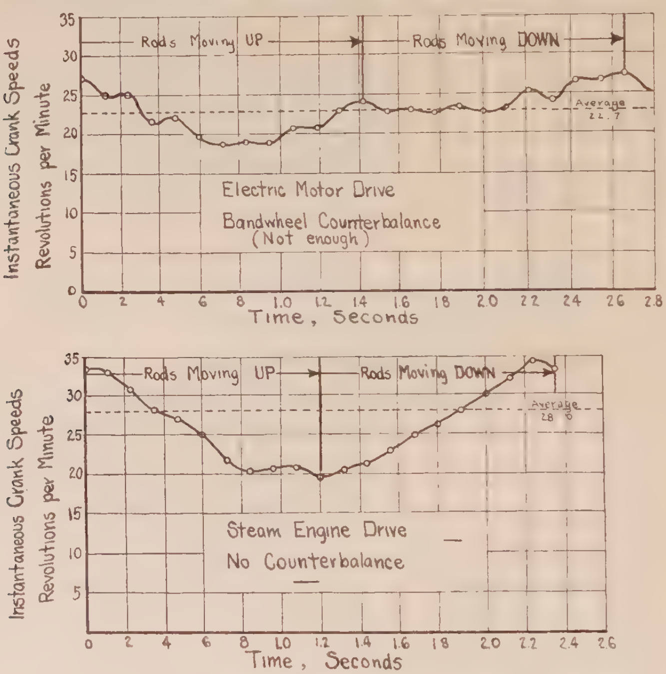

FIG. 6.—VARIATIONS OF ANGULAR VELOCITY OF CRANK.

set-up for one or more cycles. The position of the crank at every sixteenth of a second can be read from the developed film with a magnifying glass, and the differences of the readings plotted as velocities.

Fig. 7 shows the actual motion of polish rods corresponding to the crank velocity curves of Fig. 6. These curves are also derived from motion picture data, the method being similar to that for determining crank velocity. A pointer is attached to the polish rod, and moves over a vertical scale held in place while pictures are taken. Subtracting each velocity observation from the preceding velocity, and dividing by the time interval gives the acceleration.

Accelerometer and moving picture data agree fairly well, and in many cases show accelerations in the neighborhood of 100 per cent. gravity.

Such accelerations are several times greater than are theoretically necessary, and a different mechanism might substantially reduce the acceleration and resulting rod stress. A cam to take the place of the crank has been devised and tried for this purpose, but for some reason was not successful.

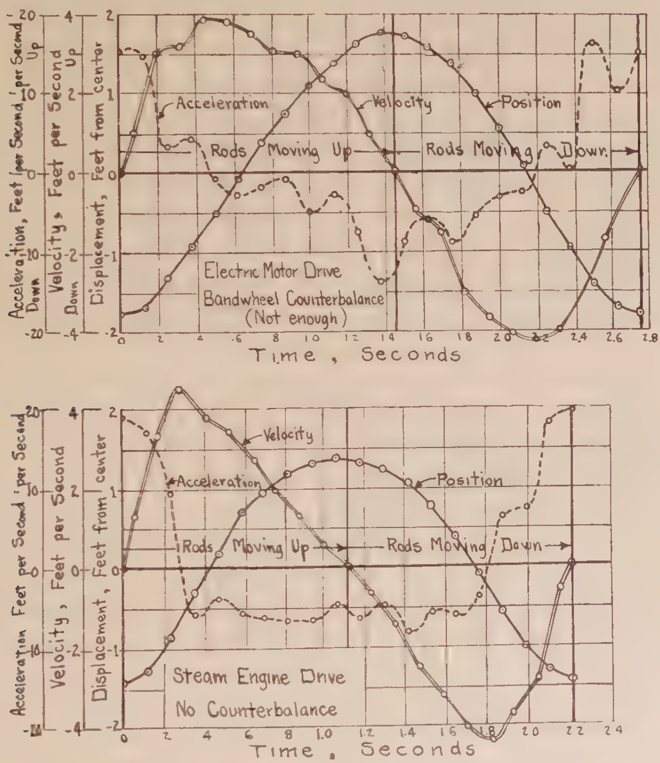

FIG. 7.—MOTION OF SUCKER RODS.

PUMPS

The pump most commonly used is the well-known type comprising a steel plunger, working in cast-iron liners which are held between shoes in a steel jacket. Ball valves are used in plunger and barrel. For the ground steel plunger is sometimes substituted one with leather cups. Recently so-called inserted pumps have come into considerable use. The feature of these is that the working barrel and standing valve as well as the plunger are pulled through the tubing on the rods. This is a real advantage in reducing the number of tubing pulling jobs. The objections to such pumps are that their size and capacity are less for any given size of tubing, and that they necessitate a leather cup plunger working in a steel barrel, instead of the generally preferred ground fit

plunger. Another special type of pump is of interest in that it comprises several loose-fitting concentric steel tubes of considerable length. Leakage is minimized by the length of the leakage path rather than the thinness of the path. Due to the loose fit, wear seems to be slower than with a ground fit pump, but tests indicate that due to the length of surface in sliding contact the friction is considerable, resulting in an increased power consumption.

Volumetric Efficiency

Volumetric efficiencies (ratio of actual gross production to apparent pump displacement based on length of stroke of beam) range from 2 to 105 per cent., and average 31 per cent. for the wells of one company. These figures include deep and shallow wells alike, the lower efficiencies applying to the shallower wells of very small production. That good volumetric efficiencies are possible under some conditions is shown not only by occasional wells with very high efficiencies, but by the fact that all of the wells in one field average 61 per cent.

Low volumetric efficiencies are due to three main causes: leakage past valves, plungers and tubing joints, displacement greatly in excess of the potential production of the well, and ineffective gas anchors. When pumps are in good condition and tubing is tight, leakage is almost negligible. A small leak may, however, cause low efficiency on wells of very small production. Low volumetric efficiency is often the result of pumping wells unnecessarily fast. In some cases it has been found that drastic reductions in pumping speed cause no reduction of production rate.

Probably the main obstacle to good efficiency is gas. Even a trace of gas, if it gets into a pump, occupies space that is thus rendered useless. For illustration, let us assume a gas-oil ratio of only 300 cu. ft. per bbl., which is a lower ratio than have 90 per cent. of California deep wells. This is 53 cu. ft. per cu. ft. Even with a submergence giving a pressure of 50 lb. per sq. in., this gas is only compressed to 12 cu. ft. per cu. ft. of oil, so that a volumetric efficiency of 1/(1 plus 12), or 8 per cent., is all that can be hoped for. Since there is always a clearance volume between the pump valves, the actual case is much worse than this. The necessity for an effective gas anchor wherever there is any gas is thus apparent.

The anchor in most common use consists of a joint of 2½-in. tubing below the pump, closed at its bottom end and perforated near its top end, inside of which is about 10 ft. of 1-in. pipe screwed into the standing valve and open at the bottom. A gravity separation of oil and gas takes place in the annular space between the two pipes. This anchor is entirely satisfactory for wells of small production and little gas, but if there is either much oil or much gas, the velocity in the downpass becomes so great that separation can not occur. In order that separation be satis-

factory, the downward velocity of mixed oil and gas in the downpass must be less than the rate of slip of gas up through oil. Most of the gas will separate if this velocity is less than 6 in. per sec., but for separation of the smaller bubbles, a much lower velocity is necessary. For wells of large diameter and good mechanical condition, anchors similar to the common one described above, but using larger pipe, are sometimes used, and gives excellent results. However, for the wells finished with small casing, or where sand or bad casing makes it inadvisable to use an anchor of larger diameter than the pump, anchors involving special features of arrangement, and more refinement of construction are necessary in order to get adequate capacity. Several of these special types of anchors are in use, and have resulted in substantial increases of production in the majority of installations.

If pumps and their auxiliaries could be improved so that good volumetric efficiency were attainable, three-fourths of all pumping wells could be slowed down to such an extent that many mechanical difficulties would almost disappear.

Conclusion

In conclusion, it may be said that pumping equipment and pumping practice is a curious mixture of the antiquated and the modern, of efficiency and inefficiency. Much of the equipment still in common use is fit only for a museum, while other equipment compares favorably with that used in the most up-to-date industries. Power efficiencies have been shown to range from 15 to 65 per cent., and volumetric efficiencies from 2 to 105 per cent. Parts of the equipment run along month after month with very little attention, and others require almost constant tinkering. California oil men have much to learn, and perhaps a little to impart, in which they are probably not much different from any other oil men.

Acknowledgments

The writer is greatly indebted to W. L. McLaine, of the General Petroleum Corpn. of California, who has made possible the preparation of this paper, and to several field men and engineers who have collaborated in the making of tests and accumulation of data upon which it is based. Among the latter should be especially mentioned J. H. Howard and B. H. Robinson.

DISCUSSION

E. H. Griswold,* Ponca City, Okla. (written discussion).—Although the features of deep-well pumping in California as described by Mr. Marsh vary in a few minor details from those of the Mid-Continent, the problems are fundamentally the same. Our Mid-Continent wells produce an oil of a much higher average gravity but are not

* Production Engineer, Marland Production Co.

bothered so much by floating sand as the California type wells. In the fields where oil gravities range from 40° to 50° A. P. I. special types of pumps have been required.

The prime movers in common use are 40 to 45-hp. two-cycle gas engines and 20 to 50-hp. electric motors. In many cases countershafts have been used between gas engine and bandwheel. These countershafts allow the engine to run close to its rated speed without excessive pumping speed and permit the use of larger drive pulleys, thus reducing the tendency for belts to bootleg. Some of the countershafts are equipped with a reverse pulley driven by a crossed belt and eliminate the use of a reverse clutch which has always been a source of considerable trouble.

Double-reduction gear and worm-gear units are coming into common use, especially where electric power is used. Large bandwheels up to 15 ft. dia. have been used with long cranks, but considerable trouble was encountered with bandwheel shafts and flanges. Gear units consisting of one gear replacing the crank with another gear attached to pitman, and connected to the crankshaft with a yoke, are being successfully used. One of these gear units has oval gears to modify the acceleration of the stroke. The principal advantage of these gear units is that they allow approximately two revolutions of the bandwheel to one stroke of the beam.

Steel pumping rigs and concrete foundations are rapidly coming into use in the deep-well areas. Mr. Marsh's comments on the over-all efficiency of pumping rigs are interesting and valuable.

My experience agrees with that of Mr. Marsh in that our present methods of counterweighting are inadequate, as no satisfactory mechanical device is yet available whereby sufficient weight may be used without undue rig strains. A definite distinction should be made between two results of counterbalancing; first, that of eliminating rod breaks and, second, that of obtaining a more uniform engine load or minimum power consumption. Some compromise must be made between the two, as in most cases the weight best suited for one will be either inadequate or excessive for the other. The ideal counterbalance is one in which the potential energy of the weight would not be changed to kinetic energy until the stretch of the rods was taken up and the beam had assumed the full load of the well.

The study of bandwheel and beam motion as made by Mr. Marsh is of the utmost value, as excessive acceleration and subsequent shock must be one of the greatest sources of rod failure. There has been considerable discussion as to whether or not a uniform angular velocity of the bandwheel is desirable. I am of the opinion that a rig should be counterweighted so as to secure a variable angular velocity of the bandwheel unless minimum power consumption or the elimination of belt trouble are of greater importance than the elimination of rod breakage.

Dynamometer charts have shown that loose rig timbers cause excessive shock loads on sucker rods. Different types and fits of pumps also have a noticeable affect. Wells that pound down or hit the fluid with the plunger show uneven rod loads which cannot help but be detrimental. The use of properly sized pump valves and anchors will decrease the number of rod breaks.

Our experience is that the frequency of rod breaks increases with the age of the string, which is contrary to Mr. Marsh's results in California. In some cases the rate of breakage shows a tendency to decrease temporarily in the early life of a string, but the general trend over a period of several months is to increase.

A great variety of pumps are in use in the Mid-Continent and no one type is universally successful. There has been considerable difficulty with the steel plunger and iron liner type due to scouring, slippage and sticking, but in many cases this type of pump is the best available. Shorter plungers and cup extensions are being widely used to eliminate lubrication difficulties in this type of pump. The bottom-hole temperatures of the deeper wells are such that cup plungers alone are not satisfactory.

The crooked hole problem is one that is giving operators much trouble. Excessive rod loads and rod and tubing wear make many deep rotary holes hard to pump. Loads up to 30,000 lb. have been encountered and rod couplings and tubing often wear out or cut through in a few days. Rod guides and specially hardened and polished rod couplings are being used with varying degrees of success.

Several central powers have been installed on wells with total depths below 4000 ft. Heavy powers with bandwheels up to 36 ft. in diameter and jacks with 6-ft. strokes are available. Many power installations are operating with loads of over 100 hp. Central powers probably will prove adaptable to deep wells that produce moderate amounts of fluid.

Pumping packers have been used to increase production and lighten pumping loads, with very good results on wells with low gas-fluid ratios.

The many important suggestions in Mr. Marsh's paper should be of great help in the solution of Mid-Continent pumping problems.

H. N. Marsh.—Mr. Griswold points out that there are two criteria of correct amount of counterbalance—minimum rig loads and power consumption, and minimum rod stress. It may be added that there is a third—minimum cost, weight and inconvenience of the counterbalance itself. Since the last two criteria conflict, the second calling for more weight than the first, and the third for less, the amount determined by the first has been accepted as a compromise, and referred to (rather arbitrarily, perhaps) as ideal. In defense it may be said that a great deal would have to be sacrificed in rig and belt loads and power consumption in order to effect a small reduction in rod stress.

This paper, in attempting to give a broad picture of typical equipment, methods and problems has omitted many interesting developments which are still in the experimental stage.

Analytical Principles of the Spacing of Oil and Gas Wells

By Robert W. Phelps,* Brea, Calif.

(New York Meeting, February, 1929)

It is gratifying to observe the growing interest in the study of oil-well spacing. It should always be held in mind that the problem of optimum spacing is to obtain the maximum return of capital per acre drained. This naturally evolves into a mathematical consideration. As mathematics is the basis of all science, an effort should be made to develop formulas which involve data obtainable in the early stages of development.

The first information from a discovery well in a new field would be the character of the sand, rate of initial production of oil and gas, viscosity of the oil, rock pressure, etc. Later, from this well, if Herold's theories of hydraulic, volumetric and capillary controls are accepted, could be determined the ultimate production as without interference from drainage by subsequent well completions, and under which control the well is producing. If it should prove to be producing under capillary control, a rough estimate could be made of its radius of drainage. With but one well, the radius of drainage, or the interference of drainage of individual wells by close spacing, would be estimated by comparison with similar conditions in other fields in which the development has progressed sufficiently to furnish the data. A second well that is spaced sufficiently close so that an interference can be observed after its ultimate production is estimated, will furnish data to develop a desirable spacing of wells which can be inaugurated for that area and which is capable of producing a uniform amount of oil under like conditions. In some fields this area will be extensive, in others each well location will require an individual study.

In 1924, Cutler[1] developed a scheme whereby he determined by tabulation a spacing of oil wells for the maximum return per acre. After a study of production in a number of fields, he developed the following as a tentative rule: "The ultimate production for wells of equal size in the same pool where there is interference (shown by a difference in the production decline curves for different spacing) seems approximately to vary directly as the square roots of the areas drained by the wells. This rule may also be stated thus: The recovery from wells of equal size

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* Petroleum Engineer, Orange Division, Union Oil Co. of California.

[1] W. W. Cutler, Jr.: Estimation of Underground Oil Reserves by Oil-well Production Curves. U. S. Bur. Mines *Bull.* 228.

producing under similar conditions in the same pool is proportional to the average distance that the oil moves to get to the well."

Subsequently, Herold[2] developed an analytical method of drainage of natural oil reservoirs. He divides producing wells into three classes; namely, those producing from (1) hydraulic, (2) volumetric and (3) capillary control. Theoretically, a well of either of the first two controls properly located in a field will drain the entire reservoir. In those cases no well spacing can be computed. In the capillary control wells, each well drains a definite area.

The scope of this paper is to develop formulas to permit computations for the proper spacing of oil wells to result in the maximum net return per acre; one based on Cutler's studies and two others based on Herold's capillary control wells. These formulas are then to be compared with hypothetical data.

Derivation on a Hyperbolic Basis

The first deduction made from Cutler's findings is that a variable amount of oil can be produced from an area by the variable spacing of wells. It is shown that the closer the wells are spaced, that is, the smaller the area each well drains, the greater will be the ultimate production from the area but less per well. Therefore, as the area of drainage per well approaches zero acres, the maximum ultimate production, or, as it will be termed here, the available production, is approached.

Let $R_\$$ = net return per acre and R_m = the maximum return per acre.

x_a = well spacing in terms of acres per well.

P_{ult} = ultimate production per acre for any value of x.

P_{av} = available production per acre.

$y = \dfrac{P_{ult}}{P_{av}}$ which is the ratio of the ultimate production per acre at x_a spacing to the available production per acre.

C_w = cost of drilling each well.

C_a = cost of drilling per acre.

V_{pav} = present value of the available production per acre including pumping costs.

F = factor so that $V_{pav} = FP_{av}$.

A and K are constants.

It is apparent that $x_a = (f)y$ and that this is a hyperbolic function. From the relationships developed from Cutler's data, the general formula is

$$y = \frac{K}{(A + x_a)^2} \tag{1}$$

[2] S. C. Herold: Analytical Principles of the Production of Oil, Gas and Water from Wells. 1928. Stanford Univ. Press.

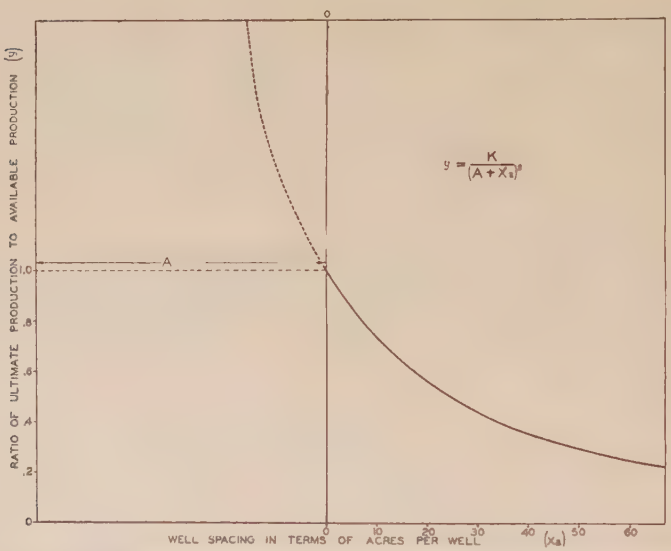

FIG. 1.—WELL INTERFERENCE AS A HYPERBOLIC FUNCTION (FROM CUTLER'S THEORY.)

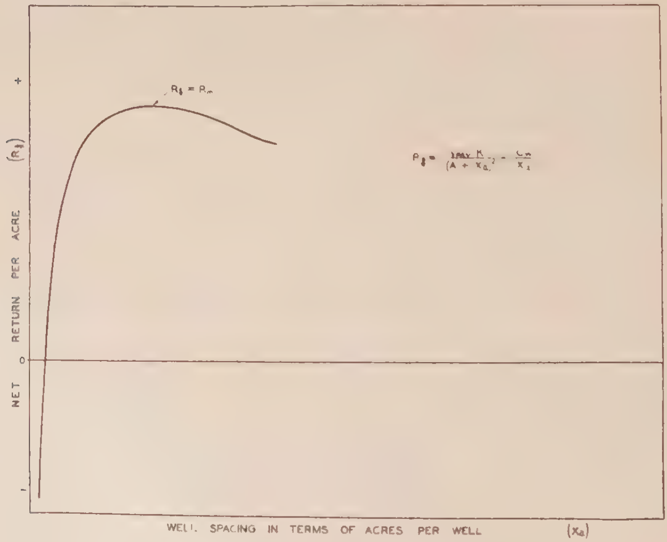

FIG. 2.—EFFECT OF WELL SPACING ON NET RETURN PER ACRE.

Fig. 1 illustrates this curve.
and

$$C_a = \frac{C_w}{x_a} \tag{2}$$

The net return is the available oil times the factor to change it to its present value, times the ratio of actual oil produced to the available production, minus the cost of drilling. Algebraically expressed, this relation is

$$R_\$ = FP_{av}y - C_a \tag{3}$$

By substitution

$$R_\$ = \frac{V_{pav}K}{(A + x_a)^2} - \frac{C_w}{x_a} \tag{4}$$

From (3) (1) and (2)

Fig. 2 illustrates this curve.

Where $R_\$$ and x_a are variables

$$\frac{dR_\$}{dx_a} = -2V_{pav}K(A + x_a)^{-3} + C_w x_a^{-2} \tag{5}$$

Simplifying and equating to zero

$$\frac{(A + x_a)^3}{x_a^2} - \frac{2V_{pav}K}{C_w} = 0 \text{ when } R_\$ = R_m \tag{6}$$

The above formula was derived in 1926.[3]

Derivation on a Capillary Control Basis

A well that has produced under capillary control to its ultimate production drains its production from within a definite radius. All of the available oil is drained from the sands immediately adjoining the well. According to Herold, the percentage of the oil drained at various distances from the well is a straight-line function until a distance equal to the radius of drainage is reached. At this point the amount of oil drained is zero.

Fig. 3 represents the drop in the percentage of available oil drained from the sands as the distance from the well increases. The oil drained from the area around a well can therefore be represented graphically as a cone, the height of the cone representing 100 per cent. of the available oil as drained immediately next to the well.

The available oil within the radius of drainage can be graphically represented as a cylinder. The height of the cylinder depicts 100 per cent. available oil and the radius represents the radius of drainage. The oil actually drained by a capillary-controlled well can be represented graphically by a cone within the cylinder of like height and radius. Therefore, an isolated capillary-controlled well can drain only one-third of the available oil within its radius of drainage.

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[3] Read before American Association Petroleum Geologists, Los Angeles Meeting, 1926, by Robert W. Phelps.

In order to study the interference of capillary wells or their graphically interfered cones, it will be necessary to define several terms. Interfered cones are cones of equal distance apart (square pattern) in which the spacings center to center are less than twice the radius of the cones.

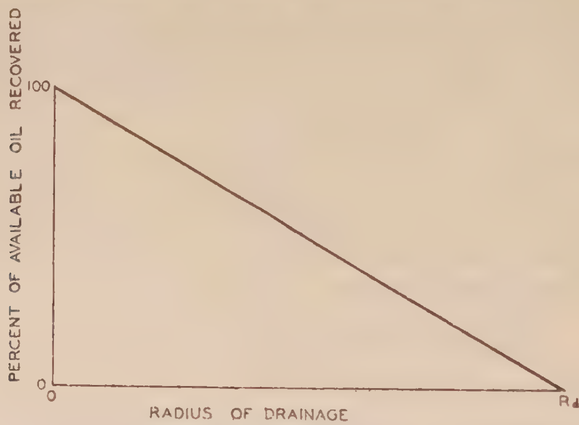

FIG. 3.—PROPORTIONAL RECOVERY OF AVAILABLE OIL WITH RESPECT TO RADIUS OF DRAINAGE.

Interfered cylinders can be defined in the same way. The residue volume of an interfered cone is that volume which is closer to the axis of the cone than to the axes of any of the adjoining cones. The residue volume of an interfered cylinder can be defined in the same way.

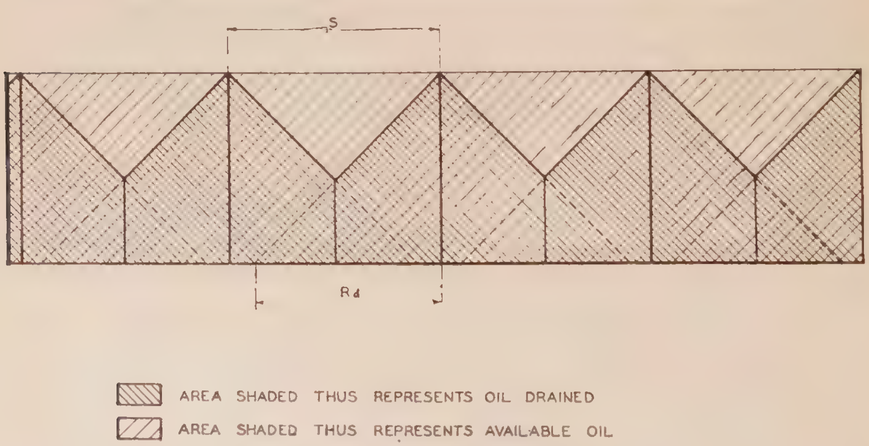

FIG. 4.—CROSS-SECTION OF GRAPHICAL CONES.

Showing interference of drainage and illustrating relation of ultimate production to available production.

It is now necessary to find the ratio of the residue volumes of the interfered cones to the residue volumes of the interfered cylinders in respect to the ratio of the well spacing to the diameter, or twice the radius

of drainage. Fig. 4 is a cross-section of the graphical cones with interference, illustrating the relation of the ultimate production to the available production. This relation for wells in a square pattern was computed by Ernsberger.[4] The results are as follows:

Let $R_\$$ = net return per acre and R_m = the maximum return per acre.

S = well spacing (distance between wells).

R_d = radius of drainage.

$$x = \frac{S}{2R_d} \tag{7}$$

P_{ult} = ultimate production per acre for any value of S.

P_{av} = available production per acre.

$y = \frac{P_{ult}}{P_{av}}$ which is the ratio of the ultimate production per acre at S spacing to the available production per acre. (8)

C_w = cost of drilling each well.

C_a = cost of drilling per acre.

V_{pav} = present value of the available production per acre including pumping costs.

F = factor so that $V_{pav} = FP_{av}$.

Between the limits of 0 and 0.707 for x it has been computed that

$$y = 1 - 0.761x \tag{9}$$

and between the limits of 0.707 and 1 for x

$$y = \frac{\pi}{12x^2} - \frac{\cos^{-1} x}{3x^2} + \frac{2\sqrt{1-x^2}}{3x} - \frac{x}{3} \log \left(\frac{1 + \sqrt{1-x^2}}{x} \right) \tag{10}$$

and when x is greater than 1

$$y = \frac{0.262}{x^2} \tag{11}$$

The last equation is without interference between the cones or wells and therefore does not enter into the problem. By substitution of equation 7 in 9

$$y = 1 - \frac{0.38S}{R_d} \tag{12}$$

Fig. 5 illustrates this interference curve.

An examination of the second section of the curve in Fig. 5, which portion represents equation 10, shows that part of the curve to be very nearly a straight line. Taking into consideration that the field data will usually be between broader limits than if this curve should be straightened, as in the dotted portion of the figure, and that equation 10 is an awkward formula to handle, it will not be outside the practical limits to use the formula for the straight line, which is approximately:

$$y = 0.945 - 0.683x \tag{13}$$

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[4] I. Ernsberger: Unpublished (January, 1929).

Substituting equation 7 in 13

$$y = 0.945 - \frac{0.3415S}{R_d}; \tag{14}$$

using the relationship expressed

$$R_\$ = FP_{av}y - C_a \tag{3}$$

and as

$$C_a = \frac{43{,}560C_w}{S^2}, \tag{15}$$

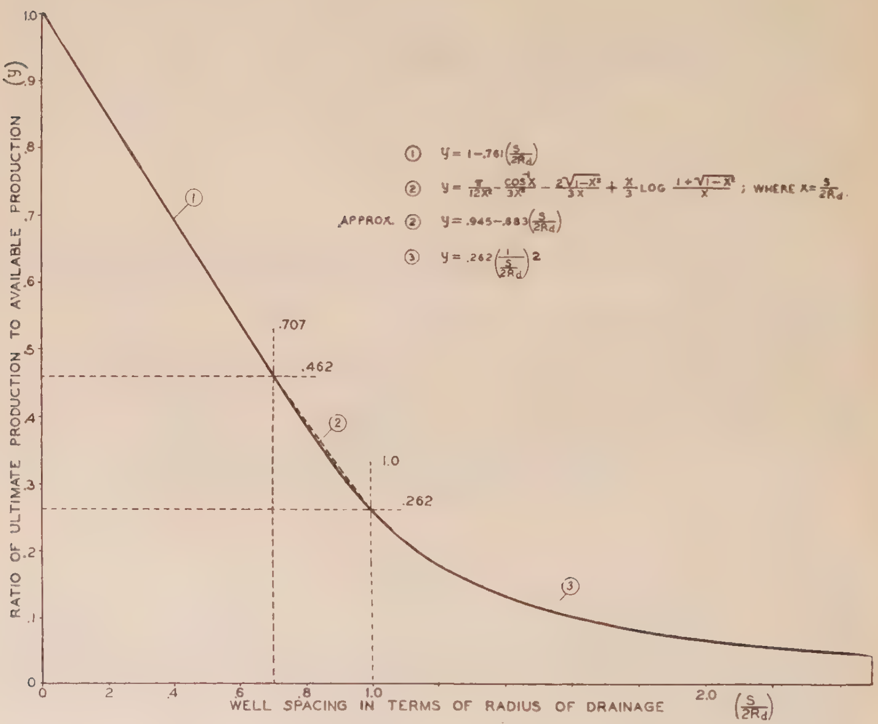

FIG. 5.—WELL INTERFERENCE CAPILLARY CONTROL (HEROLD'S THEORY).

and substituting with 12 in 3 and $V_{pav} = FP_{av}$,

$$R_\$ = V_{pav}\left(1 - \frac{0.38S}{R_d}\right) - \frac{43{,}560C_w}{S^2}, \tag{16}$$

which is the equation between the limits of 0 and 0.707 for x. Then

$$\frac{dR_\$}{dS} = -\frac{0.38V_{pav}}{R_d} + \frac{87{,}120C_w}{S^3} \tag{17}$$

Equating to zero and solving for S

$$S = 61.11\sqrt[3]{\frac{R_dC_w}{V_{pav}}} \tag{18}$$

when $R_\$ = R_m$ and the limits of x are between 0 and 0.707. By the same procedure when the limits of x are between 0.707 and 1

$$R_\$ = V_{pav}\left(0.945 - \frac{0.342S}{R_d}\right) - \frac{43{,}560C_w}{S^2} \tag{19}$$

$$\frac{dR_\$}{dS} = \frac{0.342V_{pav}}{R_d} + \frac{87{,}120C_w}{S^3} \tag{20}$$

Equating to zero and solving for S

$$S = 63.5\sqrt[3]{\frac{R_dC_w}{V_{pav}}} \tag{21}$$

when $R_\$ = R_m$ and the limits of x are between 0.707 and 1.

It will now be interesting to take data found in the field and compare the results obtained on the hyperbolic basis with those obtained on the capillary basis.

Field Application

Let us assume that in a field where it costs $85,000 to drill each well, a group of wells are so spaced that their drainage is limited to 2.81 acres (350 ft. apart) and produce to their ultimate limit 95,000 bbl. per acre, and that another group of wells are so spaced that their drainage is limited to 5 acres (467 ft. apart) and produce to their ultimate limit 88,900 bbl. per acre. The oil produced markets at $2 per bbl. and the factor for discounting the royalty, lifting costs and present value of a future profit is 50 per cent. Solution on a hyperbolic basis is as follows:

$$C_w = 85{,}000$$
$$P_{ult2.81} = 95{,}000$$
$$P_{ult5} = 88{,}900$$
$$F = 0.5$$
$$x_{5a} = 5$$
$$x_{2.81a} = 2.81$$
$$A + x_{5a} = \frac{5 - 2.81}{1 - \dfrac{88{,}900}{95{,}000}} = 68.5$$
$$A = 68.5 - 5 = 63.5$$
$$K = A^2 = 4032$$

Turning back to equation (1)

$$y = \frac{K}{(A + x_a)^2}$$ and substituting values of this problem

we have

$$y_{2.81} = \frac{4032}{(63.5 + 2.81)^2} = 0.918$$
$$y_5 = \frac{4032}{(63.5 + 5)^2} = 0.859$$
$$P_{av} = \frac{95{,}000}{0.918} = \frac{88{,}900}{0.859} = 103{,}500$$

as

$$P_{av} = V_{pav}$$
$$V_{pav} = \$103,500$$

using the equation

$$\frac{(A + x_a)^3}{x_a^2} - \frac{2V_{pav}K}{C_w} = 0 \text{ when } R_\$ = R_m \tag{7}$$

and substituting

$$\frac{(63.5 + x_a)^3}{x_a^2} = 2 \times \frac{103,500}{85,000} \times 4032 = 9830$$

$$x_a = 5.9 \text{ acres satisfies the above.}$$

Therefore $x_a = 5.9$ when $R_\$ = R_m$

Using the equation $R_\$ = \dfrac{V_{pav}K}{(A + x_a)^2} - \dfrac{C_w}{x_a}$

and substituting $R_\$ = \dfrac{103,500 \times 4032}{(63.5 + 5.9)^2} - \dfrac{85,000}{5.9} = \$67,300$

The following is the solution on a capillary control basis:

$$C_w = 85,000$$
$$P_{ult2.81} = 95,000$$
$$P_{ult5} = 88,900$$
$$F = 0.5$$
$$S_{2.81} = 350$$
$$S_5 = 467$$

Using the equation

$$y = 1 - \frac{0.38S}{R_d} \tag{12}$$

and substituting above values, we have

$$y_{2.81} = 1 - \frac{0.38 \times 350}{R_d} = 1 - \frac{133}{R_d}$$

and

$$y_5 = 1 - \frac{0.38 \times 467}{R_d} = 1 - \frac{177}{R_d}$$

$$\frac{y_{2.81}}{y_5} = \frac{95,000}{88,900}$$

$$y_{2.81} = 1.07\, y_5$$

Substituting and equating

$$1 - \frac{33}{R_d} = 1.07\left(1 - \frac{177}{R_d}\right)$$

Solving for R_d, we have $R_d = 800$ and thus the radius of drainage is found.

$$y_{2.81} = 1 - \frac{0.38 \times 350}{800} = 0.834$$

which is between 1 and 0.707 on the X axis and is in the first section of the curve in Fig. 1.

Then

$$P_{av} = \frac{95{,}000}{0.834} = 114{,}000$$

as in this problem $P_{av} = V_{pav}$ we can substitute this value in the formula

$$S = 61.1\sqrt[2]{\frac{R_dC_w}{V_{pav}}} \quad (18) \text{ when } R_\$ = R_m$$

$$S = 61.1\sqrt[3]{\frac{800 \times 85{,}000}{114{,}000}} = 515 \text{ when } R_\$ = R_m$$

$$= 6.07 \text{ acres.}$$

Using the equation

$$R_\$ = V_{pav}\left(1 - \frac{0.38S}{R_d}\right) - \frac{43{,}560C_w}{S^2} \tag{16}$$

and substituting the above values

$$R_m = 114{,}000\left(1 - \frac{0.38 \times 515}{800}\right) - \frac{43{,}560 \times 85{,}000}{515^2} = \$75{,}000.$$

Comparison of Methods

There is relatively small difference in the results. Computing the proper spacing on the hyperbolic interference curve we get 505 ft., or 5.9 acres, to the well in comparison to the capillary control interference curve with which we get 515 ft., or 6.1 acres, to the well, a discrepancy of only 2.8 per cent. The maximum return per acre by the hyperbolic interference curve is \$67,300, against \$75,000 for the capillary control, the discrepancy amounting to 10 per cent. These discrepancies are well within the limits of error of the familiar and accepted methods of estimating the value of the ultimate production and the cost of drilling wells.

A good comparison of the result of the two methods of determining the net return for various spacing of wells is shown in Fig. 6. The field data are given in the second line of Table 1 and where lacking are the same as in the problem before. It is interesting to note that the two curves are nearly identical. This curve shows that the maximum net return per acre is approximately \$100,000 at a spacing of 5 or 5.1 acres. It also develops that any spacing between 6 or even 7 acres to the well brings but very little less than the maximum net return per acre.

A further comparison of the two bases for computation is worthy of thought. Let us assume we have the same field data as above except that we have an increase in the ultimate production, but in the same ratio as 95,000 and 88,900 to preserve the same characteristic curves. A study of Table 1 develops that there is a great change in the proper well spacing.

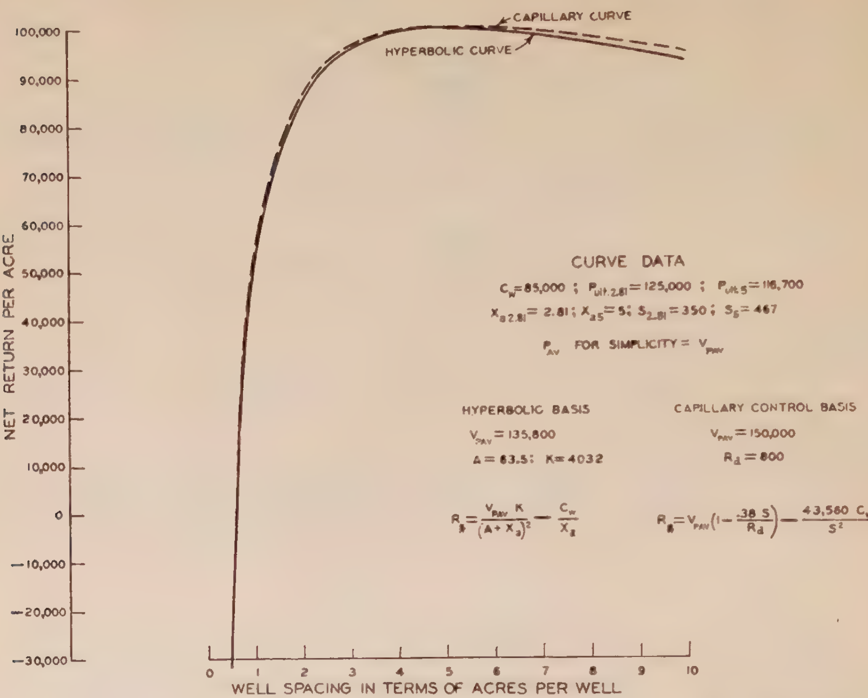

FIG. 6.—COMPARISON OF NET RETURNS COMPUTED ON HYPERBOLIC AND CAPILLARY CONTROL INTERFERENCE CURVES.

TABLE 1.—*Comparison of Two Bases for Computation of Oil-well Spacing*

Ultimate Production per Acre with Spacing		Spacing at Which Maximum Return Is Obtained			
		Hyperbolic		Capillary Control	
2.81 Acres per Well	5 Acres per Well	Acres per Well	Spacing, Ft.	Acres per Well	Spacing, Ft.
95,000	88,900	5.9	505	6.1	515
125,000	116,700	5.0	467	5.1	470
250,000	233,200	3.4	385	3.2	372
500,000	460,000	2.35	324	1.94	291
1,000,000	934,000	1.64	267	1.22	231
2,000,000	1,867,000	1.14	222	0.77	183

It is apparent that the greatest factor in planning for proper spacing of wells is the ratio of the cost of drilling to the value received from the wells. Fig. 7 illustrates Table 1 and further depicts the closeness of the values of best well spacing by the two methods and the net return is greatly influenced by any change in the value of the ultimate production.

Conclusions

A fairly accurate estimate can be made in the early development of an oil field for the proper spacing of oil wells for the maximum net return per acre. A study of adjacent fields, including the available production per acre, thickness and porosity of the producing horizons, viscosity of the oil, probable radius of drainage, and the characteristic interference

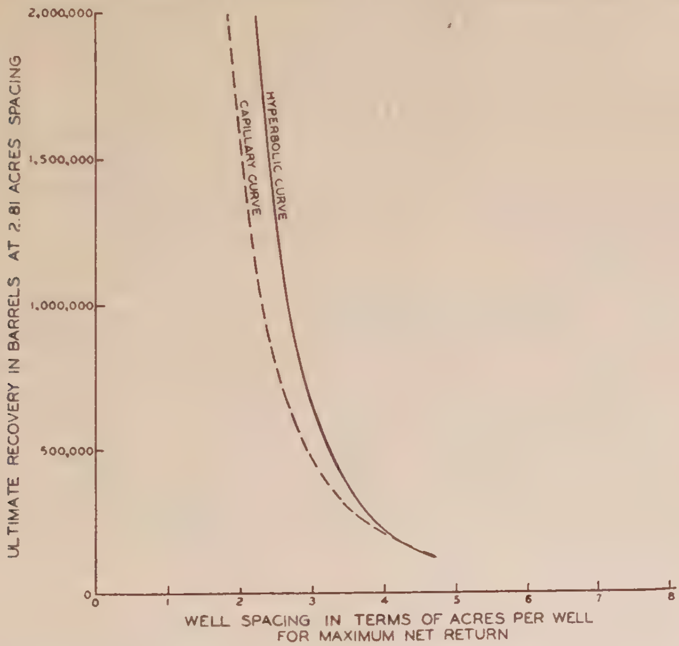

Fig. 7.—Ultimate production curves.

Curves show that ultimate production is an important factor in well spacing. They also show close relation between hyperbolic and capillary basis of computation.

curves, can furnish sufficient data to permit an intelligent estimate for well spacing. The two greatest factors that influence the spacing of oil wells are the cost of drilling each well and the value of the available production. Great differences in the radius of drainage will greatly influence the spacing of wells. The maximum net return per acre varies a diminishing amount as the most favorable spacing is approached which gives sufficient latitude for most errors from field data.

Acknowledgments

There were several persons who materially aided in compiling and assembling the data in this paper. I wish particularly to thank F. W. Lake who read the paper and offered constructive criticism as to pre-

sentation as well as checking the logic of the mathematical reasoning, V. Kalichevsky who checked the mathematics of the formula derived from the hyperbolic function, Iva Ernsberger who developed the interference relation between interfering cones, Lyle Dillon who checked the mathematics and details of the problems and made some of the drawings, and M. E. Baird who made a number of the drawings.

DISCUSSION

R. W. Phelps.—The purpose of this paper was to develop a formula, or formulas, for the spacing of oil wells; further, so that field data for the premises for the formula could be obtained early in the development of the field. It was not the purpose of this paper to go into details of obtaining these data, but as there appears to be considerable doubt as to the possibility of obtaining practical data, I will outline a method which is quite dissimilar to the two interfering wells of Herold's method of determining the radius of drainage.

Data have been published[5] regarding spacing of wells in the Meyer zone in Santa Fe Springs field, California, in which there were 4.35 acres per well having a total ultimate production of 97,500 bbl. per acre in contrast with an adjoining tract of spacing of 0.66 acres per well that will produce an ultimate production of 492,000 bbl. per acre. These data are sufficient to make an estimate of the available oil as being equal to 735,000 bbl. per acre. The average radius of drainage was computed and found to be 155 ft. This appears to be a very small distance, but is supported by the fact that 735,000 bbl. per acre, the available oil, is equal to 12 per cent. of the total volume of each acre of the Meyer zone based on a thickness of 800 ft. There is no reason, that I can observe, why the newly discovered underlying zones cannot be assumed to have a radius of drainage of nearly equal distance.

J. R. Suman,* Houston, Tex.—I consider this question of well spacing the most important question before the oil industry today. The engineers and economists who have been working in oil have gotten around to the conclusion that the Utopia in the oil business is a unit operation where all the leases are amalgamated and one company operates the entire property, and assuming for the sake of argument that we had a lot of those ready on which to go to work, who knows how to develop those properties and space the wells and get the maximum utilization of the gas energy in the structure and the maximum return on investment?

If you dissipate the gas energy in the structure in two years, you leave oil that can probably never be recovered, even if you wait 20 years. You cannot get the oil after the gas energy is dissipated, and if you do not make it do the maximum amount of work, you will not get the maximum results. You can only intelligently develop a unit operation, which is what we would all like to see come to pass in the oil industry, if you can solve this question of well spacing. It is the most important and vital subject before the industry.

R. W. Phelps.—Mr. Suman amplifies in my mind that the radius of drainage of oil is less than the radius of drainage of the associated gases.

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[5] American Petroleum Supply and Demand. Report to A. P. I.

* Director Production Dept., Humble Oil & Refining Co.

H. C. Miller,* San Francisco, Calif.—This work on well spacing will also have to take into consideration the possible advantages of repressuring. In other words, a field might be widely spaced and later repressured and the net return would be greater than from one closely spaced and not repressured, so that I think all formulas should take into consideration not only repressuring but gas drive or water drive or any other method of bringing the oil out.

Also, we must take into consideration producing methods. Should these formulas be considered as applying only when the oil is being produced most efficiently, that is, getting the most work out of the gas, or will they apply when the well is producing in haphazard condition, or if one man is producing efficiently and his next door neighbor in his offset well is producing inefficiently? There is more to well spacing than has been brought out and I am very much in doubt whether we shall ever be able to formulate well spacing except for certain conditions. All well-spacing problems must take future producing methods into consideration.

R. W. Phelps.—The formulas derived in this paper are not applicable to repressuring. We must learn more of the added recovery by repressuring and its relation to well spacing before an analysis can be made.

These formulas are based on uniform production methods. Any variation in the efficiency of production will cause a variation in the radius of drainage. One is a function of the other. Herold has analyzed this phase completely. It would be well that we catch up with our well-spacing problems based on present-day production methods before we worry about the effect of future production methods.

K. C. Heald,† Pittsburgh, Pa.—We need more variables; in the past we have not had anything. If so many variables and conditions are so uncertain, what excuse is there for drilling every field with 10-acre spacing rather than trying to find out what the conditions are and trying our best to meet those conditions? The development of these formulas looks forward to getting away from the matter of spacing controlled absolutely by the size of block, and the need for the formula is apparent to everyone who has studied the oil fields of the United States, when the greatest oil field of the Gulf Coast, the Humble field, which has yielded more oil than any other field in the Gulf Coast, has yet failed to yield enough oil even to pay the cost of drilling the wells and lifting the oil yielded by that field. That shows there is something the matter, and it is very serious.

R. W. Phelps.—The essential variables such as viscosity, initial rock pressure, size and shape of reservoir interstices, gas-oil ratio, efficiency of production, etc., can be considered constant for any province and are grouped into the constant, radius of drainage. The latter can be estimated within the range of economic limits.

C. V. Millikan,‡ Tulsa, Okla.—I doubt if we can ever solve problems of well spacing by mathematics alone. Judgment based on experience must be used in the application of mathematical formulas. Prior to 12 or 15 years ago, estimates of ultimate production of an area were based on experience and usually expressed in barrels per acre. Then decline curves were developed, which is a mathematical method of estimating production. Decline curves do not solve the problem but they do give a better working basis than the rule of thumb, barrels per acre.

R. W. Phelps.—I concur with Mr. Millikan that mathematical procedure must be dominated by intelligence and that the rule of thumb bases are only makeshifts.

* Petroleum Engineer, U. S. Bureau of Mines.

† The Gulf Oil Companies.

‡ Amerada Petroleum Corpn.

Pressure Control of Oil Wells*

By E. H. Griswold† and W. J. Wilkins,‡ Ponca City, Okla.

(Tulsa Meeting,§ October, 1928)

Pressure control of oil wells may be defined as the adjustment of pressures within a well to obtain the most efficient and economic utilization of the natural gas energy with a minimum of sand troubles or irregular water encroachment. The purpose of this paper is to present the methods used by the writers in applying pressure control and a discussion of the various effects occurring within the wells affected. The benefits to be derived from the conservation of natural gas energy have been so adequately discussed and demonstrated in prior papers by various engineers that the effects on ultimate production will not be discussed other than to mention a few representative cases. The detrimental effects of irregular edge-water encroachment and of sanding up are of general knowledge to the industry.

Effect on Ultimate Production

One of the strongest objections voiced against pressure control is that of the danger or inadvisability of deferring oil production by cutting the rate of production. It has been our experience that such deferred production is returned within a few weeks or months rather than years and that an increased cumulative oil production is obtained in the early life of the well by conserving the natural energy. In many cases the rate of production is increased rather than decreased by the adjustment of pressures to obtain the minimum gas factor.

Fig. 1 shows the history of a Wilcox sand well in northern Oklahoma, which was pressure-controlled from completion. It is noted that during the early months while flowing naturally through the casing the gas factor was decreased rather than allowed to follow its natural tendency to increase. A string of 2½-in. tubing was run to restrict the flow and resulted in a decreased gas factor with a more sustained rate of production. When first placed on gas-lift the gas factor again tended to increase, but after the proper pressure adjustments were made, remained approximately steady. It was necessary to defer 100 bbl. per day of oil production in order to maintain this low gas factor. In March serious

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§ Meeting of Mid-Continent Section, A. I. M. E.

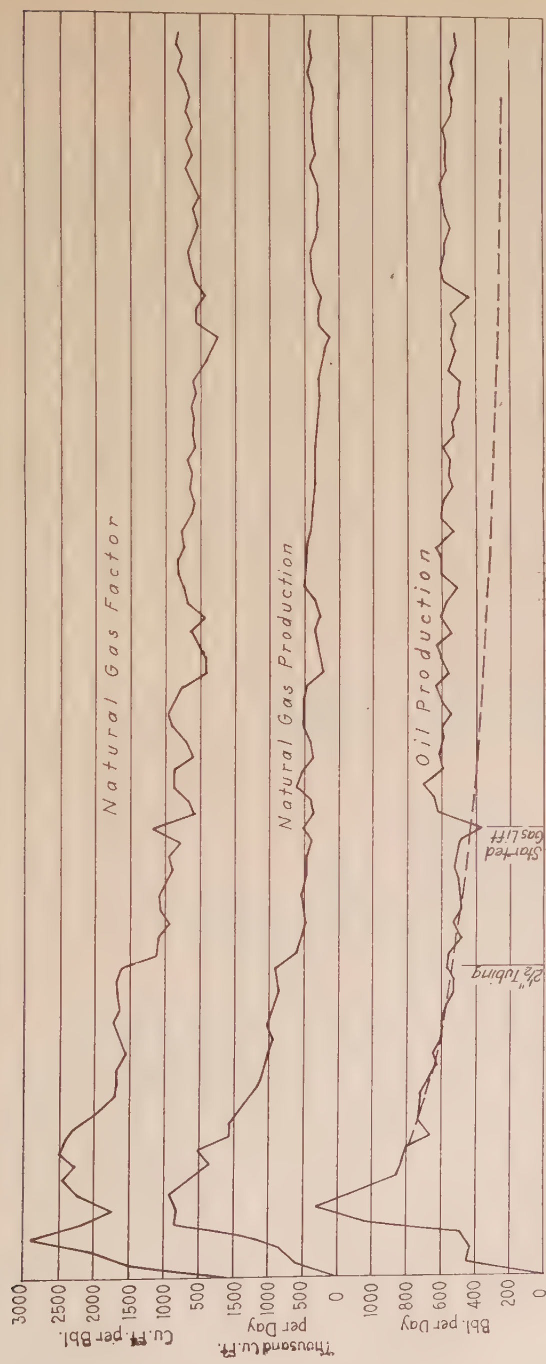

FIG. 1.—HISTORY OF A WILCOX SAND WELL IN NORTHERN OKLAHOMA, PRESSURE-CONTROLLED FROM COMPLETION.

sanding up was encountered, but this was remedied in April by a method to be discussed later, and a resultant gain in production obtained. The manner in which this well has held up in comparison to offset wells has more than justified the methods used.

Fig. 2 is an example of a well on which pressure control by use of properly sized flow string gave an increase of 100 bbl. per day in rate of production with a corresponding decrease in gas factor. Subsequent pressure adjustments at the well head in May after the well had declined

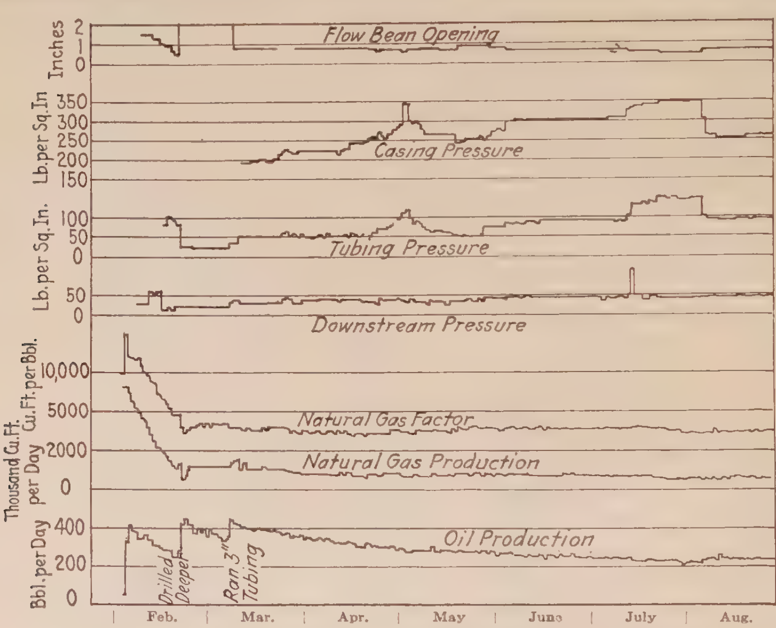

FIG. 2.—PRODUCTION DATA FOR WELL ON WHICH PRODUCTION WAS CONTROLLED BY PROPERLY SIZED FLOW STRING.

to 275 bbl. per day resulted in a sustained rate of oil production as shown by the rate-cumulative curve of Fig. 3, although scarcely evident on the decline curve of Fig. 2.

Cooperation of offset well owners is beneficial but not always necessary for the use of pressure control even when production is deferred. An interesting test of this was made on two offsetting Wilcox sand wells. Well *X* was completed with an initial production of 1300 bbl. and well *Y* with an initial production of 700 bbl. Both wells had the same thickness of sand but well *X* was somewhat better located structurally. Well *X* was produced at its maximum rate without regard to gas factor, while well *Y* was pressure-controlled by deferring production to maintain the minimum gas factor. At the end of approximately one year well *Y* had a larger cumulative production than well *X* despite the great difference in initial and flush production.

There are undoubtedly areas in which sand conditions are such that economic considerations will not permit deferring production unless operators cooperate, but in all instances the operator will be repaid for testing his wells to determine the point of minimum gas factor obtainable at the rate of production deemed necessary to prevent loss by drainage.

There has been some doubt expressed as to the relation of the minimum gas factor to the most economical gas factor from the viewpoint of ultimate profit. In some instances it is possible to produce a well at such a low rate that the producing life and operating cost may be increased

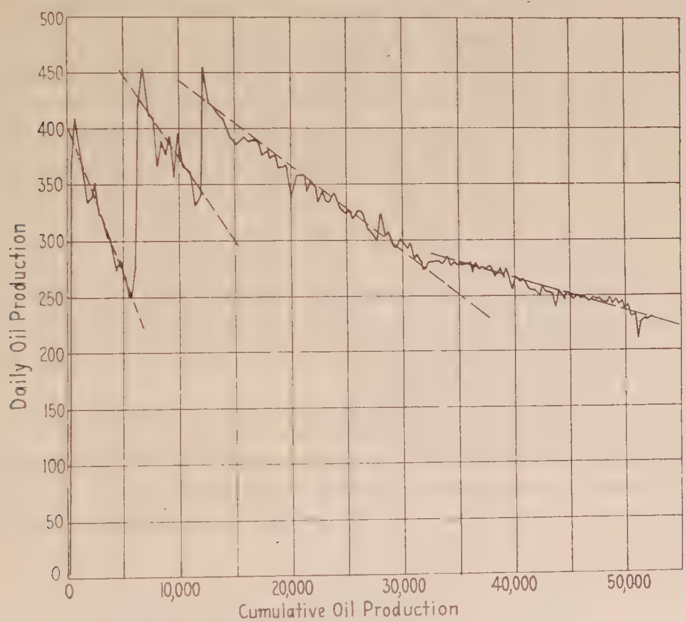

FIG. 3.—RATE CUMULATIVE CURVE FOR WELL SHOWN IN FIG. 2.

to where they would offset the gain in ultimate production. However, in the great majority of cases, the point of minimum gas factor so closely coincides with the most economical gas factor, that the distinction cannot be made within the accuracy of the governing elements.

APPLICATION OF CONTROL METHODS TO FLOWING WELLS

In applying pressure control to either naturally flowing wells or gas-lift wells the major adjustment is that of proper size and depth of flow tubing. The minor adjustments are made by variation of input gas on gas-lift wells and by back-pressure at the flow line on both types of wells.

It has been found that surface flow line design and separator location have a marked influence on the results obtainable, especially when high

back-pressures are used. The stratification of oil and gas in the flow line with attendant slippage can cause excessive gas factors and thus waste either natural or supplied energy and in some cases both. A properly designed flow line is one in which all bends are convex upward. In one case a change in flow-line curvature from upward concavity to upward convexity gave an increase of 20 per cent. in fluid lifted with a corresponding decrease in gas factor as gas volumes remained constant. In another case a change in location and elevation of a separator gave a 21 per cent. increase in oil production without change of gas volumes.

The use of adjustable needle-valve flow beans is preferred to high back-pressures on separators, as flow-line slippage can be overcome by the expansion of gas after passing through the bean. The bean should be placed close to the well head and the downstream pressures maintained low enough to give critical velocity through the bean, insuring constant pressure regulation, and preventing slippage back through the bean. A definite case of slippage through a flow bean was encountered when holding an upstream pressure of 500 lb. and a downstream pressure of 420 lb., on a well flowing 80 bbl. of oil and 1200 M. cu. ft. of gas through 6¼-in. casing. When the downstream pressure was reduced the bean was closed to maintain the 500 lb. upstream pressure. Reducing the downstream pressure to 380 lb. increased oil production 100 per cent. without changing the gas production.

Tubing packers set low in the hole are preferable on naturally flowing wells which produce small volumes of gas and oil, as wells of this type start more easily and flow more steadily than when packed off at the well head. On larger wells, packing off at the head is advisable for both mechanical and control reasons.

Gas-lift as a Pressure-control Method

Gas-lift has proved to be the most flexible and satisfactory method of controlling pressures within a well. Wells that flow naturally can often be gas-lifted with much lower natural gas factors and without decreasing the rate of production. The energy thus conserved more than compensates for the increased operating cost. Wells that appear similar in all respects may be affected differently as to natural gas factor when changed from natural flow to gas-lift without regard to gas conservation. The proper time for such a change may be estimated accurately from test data taken while flowing naturally through tubing packed off at the head. On wells flowing through casing, an indication of the time for change can be had by noting the sensitivity of the well to back-pressure adjustments, but in many cases can be positively ascertained only by gas-lift installation and subsequent pressure and volume experiments.

Tubing Design

The determination of the proper size or sizes of flow tubing for either naturally flowing or gas-lift wells is a problem to which the writers have found no satisfactory mathematical solution. The use of tapered tubing has not been advocated until such a formula is available, as the benefits obtained do not compensate for the risk of running an improperly tapered string. The proper size of a string of straight tubing can be estimated with fair accuracy from the results obtained on similar wells and can be positively ascertained by a pressure test after installation, when both tubing and casinghead pressures are available. The depth of tubing is an important adjustment in gas-lift wells with high working fluid levels, and in naturally flowing wells with high gas factors. In the former case, submergence must be adjusted to obtain the desired bottom-hole pressure, while in the latter case, entry losses and slippage are thought to be the controlling factors.

Control Tests

Tests can be made to determine the suitability of the installed flow tubing, the proper outlet pressure adjustment, and in the case of gas-lift

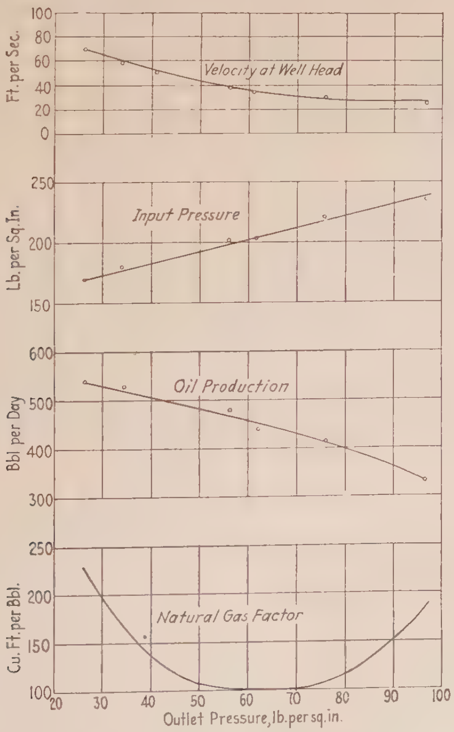

Fig. 4.—Pressure-control test on gas-lift, central flow well; 3-in. tubing; 740 M. cu. ft. gas input volume held constant.

wells, the proper input volume. All three of these adjustments are interdependent and must be combined in a correct relationship. On naturally flowing wells the outlet pressure is varied throughout the required range, to obtain the resultant changes in oil and gas production. On gas-lift wells the input volume is varied while holding the outlet pressure constant at each of several pressures, and then the outlet pressure varied while holding each of several input volumes constant. By taking

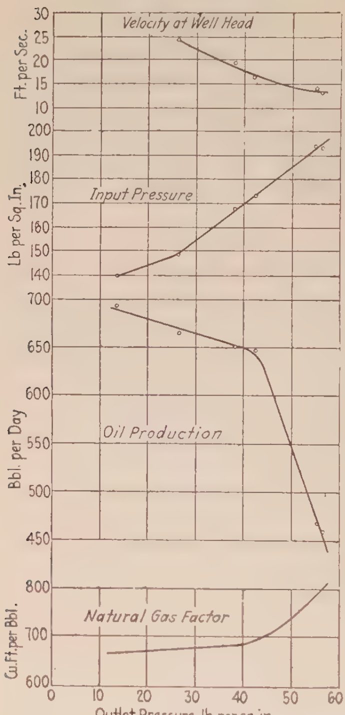

FIG. 5.—PRESSURE-CONTROL TEST ON GAS-LIFT, ANNULAR FLOW WELL; 6⅝-IN. CASING; 2½-IN. TUBING; 550 M. CU. FT. INPUT VOLUME HELD CONSTANT.

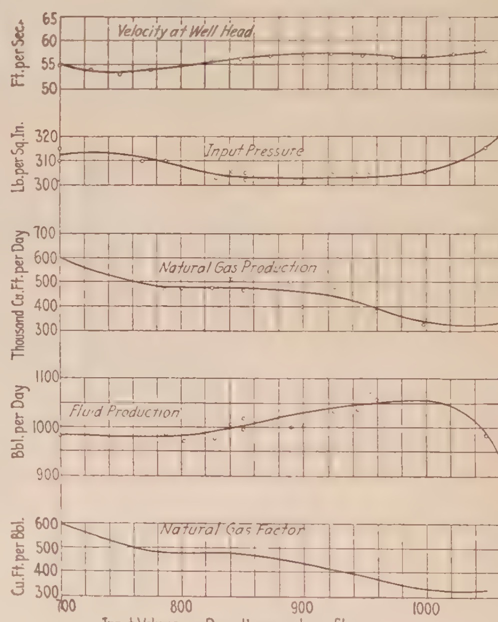

FIG. 6.—PRESSURE-CONTROL TEST ON A GAS-LIFT, ANNULAR FLOW WELL; 5$\frac{3}{16}$-IN. CASING; 2-IN. TUBING; 25-LB. OUTLET PRESSURE HELD CONSTANT.

accurate measurements of oil and gas production, the point of minimum gas-oil ratio is obtained.

The trend of the curves plotted from these data indicate the suitability of the tubing size. The major indication of too large a tubing is a sharp downward break in the oil-production curve when plotted against outlet pressure. Too small a tubing is indicated when the oil production is gradually decreased by increasing the outlet pressure but the natural gas factor simultaneously increased. In making this determination on

gas-lift wells, the data used should be that obtained with the most satisfactory input volume.

The time required for making these tests on flush wells or wells with low natural gas factors is surprisingly short. It has been found that by making the pressure adjustments in small increments these types of wells arrive and settle down at their new condition within a few hours so that sufficient data can be obtained within 3 or 4 days. Old wells and wells

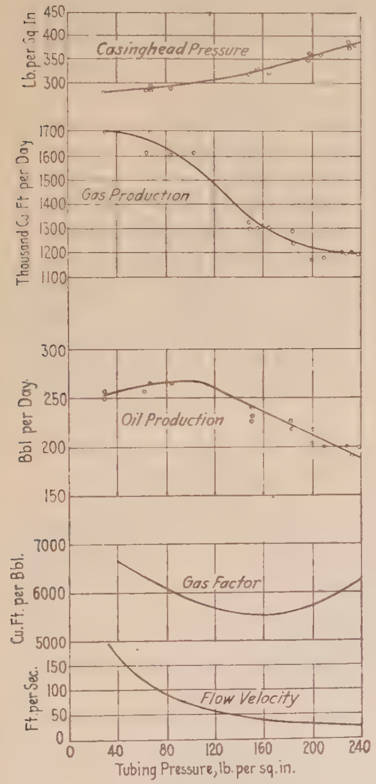

FIG. 7.—PRESSURE-CONTROL TEST FLOWING THROUGH 5125 FT. OF 2½-IN. TUBING; BACK-PRESSURE HELD ON SEPARATOR.

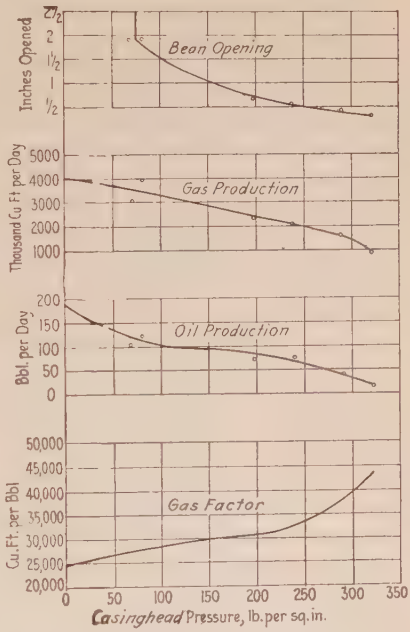

FIG. 8.—PRESSURE-CONTROL TEST; TOP OF SAND, 1809 FT.; 8¼-IN. CASING SET AT 1758 FT.; 6⅝-IN. LINER SET AT 1810 FEET.

with high gas factors require considerably more time to settle down to new conditions. In these cases the normal rate of decline is low enough not to affect the accuracy of the test and plenty of time is usually available. When flush wells are declining noticeably the oil and gas production data may be plotted in per cent. deviation from the projected normal curves rather than in absolute values, with satisfactory results. The importance of accurate oil and gas production measurements cannot be overemphasized while making these tests.

Figs. 4 and 5 show tests made on different types of gas-lift wells by varying the outlet pressure. Fig. 6 shows the results obtained by varying the input volume of a gas-lift well while holding the outlet pressure constant. Figs. 7 and 8 are pressure-control tests on wells flowing naturally.

In Figs. 5 and 8[1] the natural gas factor was increased by the application of back-pressure, and in Figs. 4 and 7 back-pressure above certain limits increased the natural gas factor. This is conclusive evidence that a well cannot be pinched indiscriminately to any desired rate of production without the risk of simultaneous waste of gas energy and a resultant decrease in ultimate recovery of oil.

Pressure Control of Pumping Wells

The gas factors of pumping wells have been varied over wide ranges by the control of fluid levels and also by the use of pumping packers. Fluid levels have been controlled successfully by changing pump submergence and by changing the rate or period of pumping. Pumping packers have been used to decrease the bottom-hole pressure on wells which cannot be pumped off. There is need for more data on pressure control of pumping wells, particularly on those producing from thick sands with low rock pressures.

Pressure Control of Water Encroachment

In the majority of flowing wells, approach of edge water is indicated by a sharp rise in flow temperature and a tendency for the natural gas factor to decrease spontaneously. Allowances must be made in the interpretation of flowing temperatures for changes in temperature of input gas on gas-lift wells. Changes in back-pressure also change temperature readings due to gas expansion and must be discounted.

Where temperature or gas factors indicated the approach of water, the highest back-pressures, permissible with low gas factors, have been held with ostensibly excellent results, as these wells did not go to water as fast as similar but uncontrolled wells. Results of this kind cannot be conclusive as there is no suitable basis for absolute comparison, but they are at least strongly indicative.

After wells start producing some water, the water-oil ratio often may be varied appreciably by pressure control. In one case a well which was swabbing 50 bbl. of water with 600 bbl. of oil was placed on the gas-lift and the water entirely eliminated for 23 days, even though the oil production was increased to 700 bbl. per day. In many cases the water-oil ratio has been decreased materially and held down through control of bottom-hole pressures by changing submergence or outlet pressures.

[1] Personal communication from George L. Nye, Marland Production Co.

Fig. 9 presents the pressure control test of a naturally flowing well which was making water. It is noted that although the rate of water production was decreased by back-pressure, the water-oil factor was increased. The change in rate of increase of this water-oil factor closely correlates with the point of minimum gas factor. It has been found that in most cases, the points of minimum factors roughly coincide so that a decision is not often required as to whether a well should be produced with a minimum gas-oil factor or a minimum water-oil factor.

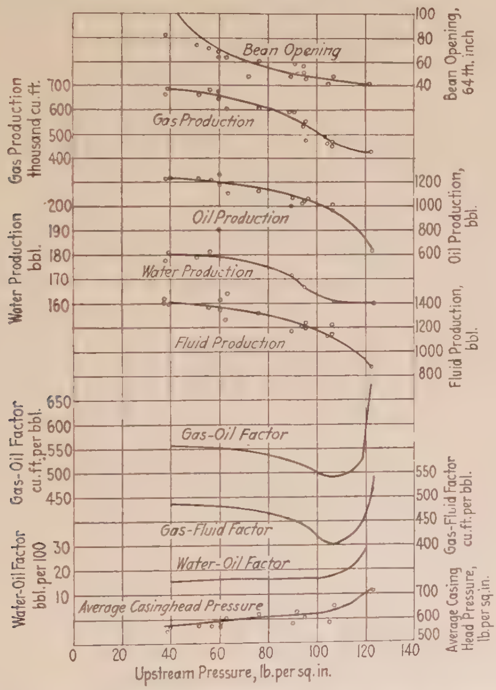

FIG. 9.—PRESSURE-CONTROL TEST FLOWING THROUGH $2\frac{1}{2}$-IN. TUBING; TOP OF SAND, 4282 FT.; TUBING AT 4255 FT.; CAGE BETWEEN FIRST AND SECOND JOINTS.

METHODS OF CONTROLLING SAND TROUBLES

Wells making excessive amounts of sand can often be handled economically by increasing flow velocities to a point where the sand can be removed. The use of gas-lift has been most satisfactory for this purpose as high velocities can be obtained without necessity of serious alteration in pressure conditions.

A method of cleaning out flowing wells by circulation has been found to be adaptable where periodic formation caving is encountered. Water was lubricated into the input gas in slugs of 2 bbl. each. This water caused emulsions to form in the bottom of the hole. The viscosity and density of the emulsions were such that they removed the cavings from

the hole. Fig. 10 is the production and control data for the later life of the well shown in Fig. 1. Early in February the accumulation of cavings in the hole caused the input pressure to increase rapidly with a corresponding decrease in oil production. Heat-generating chemicals were lubricated into the input gas as the well appeared to be choked with paraffin. Successful results were obtained with the chemical as the pressure immediately returned to normal. After two more similar treatments it was found that the water introduced with the chemical was alone responsible for the benefits obtained and in successive cases water only was used.

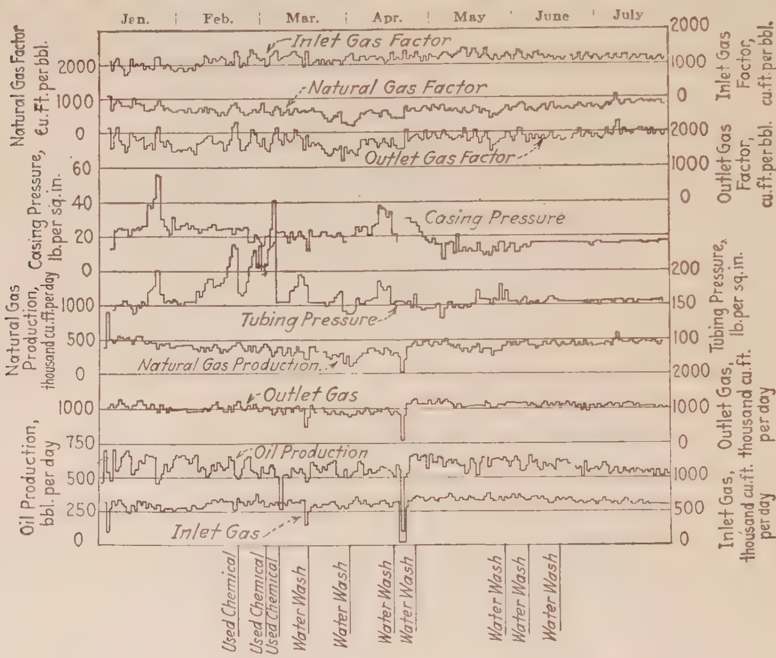

Fig. 10.—Production and control data for later life of well shown in Fig. 1.

The use of this method avoided an expensive and detrimental cleaning-out job and is believed to have prolonged the gas-lift life of the well by at least 6 months, as the well is still producing approximately 400 bbl. per day on gas-lift.

Breaking-out Pressures

It has been found that in many cases uninterrupted operation is essential to long life on gas-lift. Wells that have been frequently shut down and started with high pressures have not given results equal to those that were kept in continuous operation. Wells may be permanently injured by high starting pressures. Unloading with a swab or breaking out by stages is recommended for use in cases where this danger

exists, as a few hours' extra production will not compensate for the possible damage.

Effects of Outlet Pressure on Flow Column and Subsequent Bottom-hole Pressures

Some of the data taken within the course of operation and testing of wells have supplied interesting indications of what happens within a well when pressure is applied at the outlet. Conclusive evidence has been

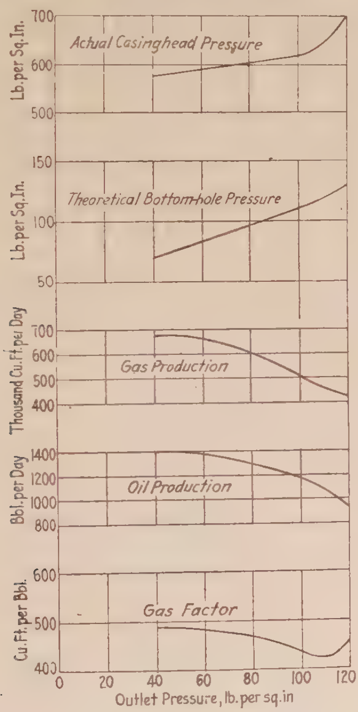

Fig. 11.—Actual back-pressure and calculated pressure to flow gas only, from well with low gas factor, through $2\frac{1}{2}$-in. tubing.

obtained regarding the presence of working fluid levels in wells with low gross gas factors. In these wells there is a constant column of oil in the hole through which the gas bubbles and from the top of which the oil produced is picked up as a spray. In one well flowing 20 bbl. per hr. naturally with a gas factor of 550 cu. ft. per bbl. the pressure at a depth of 3200 ft. was found to be 820 lb., while at a depth of 3600 ft. it was over 950 lb., a difference of 130 lb. per sq. in. for a 400-ft. column of fluid. When the fluid column was lightened by the circulation of gas the pressure at 3200 ft. was only 300 lb. although the oil production increased to 30 bbl. per hour.

The working fluid level may be raised or lowered by changing the velocity of flow. In this case the bottom-hole pressure is not affected directly by the outlet pressure, but is affected by the flow slippage due to velocity which is controlled by the outlet pressure. This slippage affects the height of fluid level which automatically regulates bottom-hole pressure to the point where an amount of oil, capable of being lifted at a corresponding velocity, is produced. An example of this case is shown

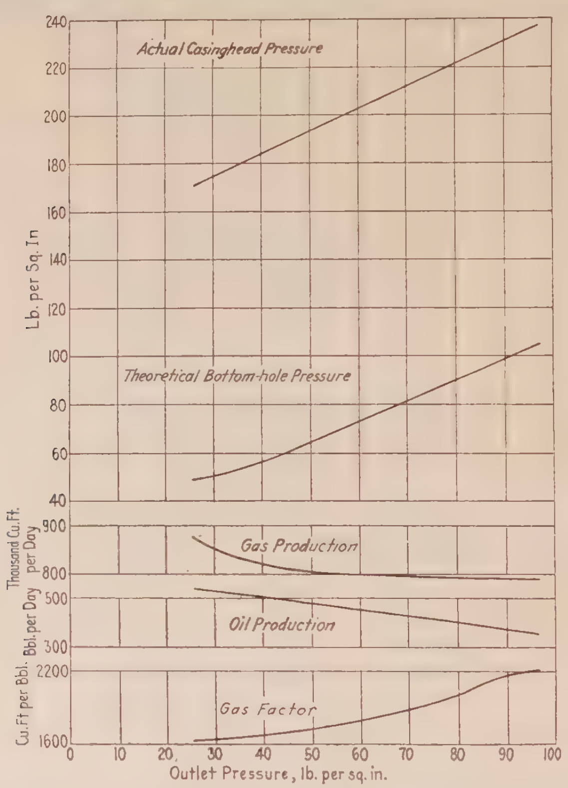

FIG. 12.—ACTUAL BACK-PRESSURE AND CALCULATED PRESSURE TO FLOW GAS ONLY, FROM WELL WITH MODERATELY HIGH GAS FACTOR, THROUGH 3-IN. TUBING.

by Fig. 11, which shows a comparison of casinghead pressure used as an index to the trend of bottomhole pressure, and the calculated pressure required to flow the gas only. Above approximately 100 lb. outlet pressure, the casinghead pressure increases rapidly while an enlarged scale is necessary to notice the difference in trend of theoretical pressure. It is thought that slippage was obtained at about 100 lb. outlet pressure where the well-head velocity was approximately 26 ft. per sec. and the bottom-hole velocity approximately 6.5 ft. per second.

Figs. 12 and 13 present data on wells with higher gas factors and velocities, plotted similarly to Fig. 11. The trend of the theoretical

and actual pressures are almost identical on each of these wells which would indicate that no working fluid level is present. Fig. 13 is particularly interesting in that a decrease in bottom-hole pressure gave a decrease in gas production. This is thought to have been caused by oil blocking off gas passages in the sand following the pressure change.

A study of flow velocities has indicated a hyperbolic relationship between the velocity at the well head corresponding with the point of

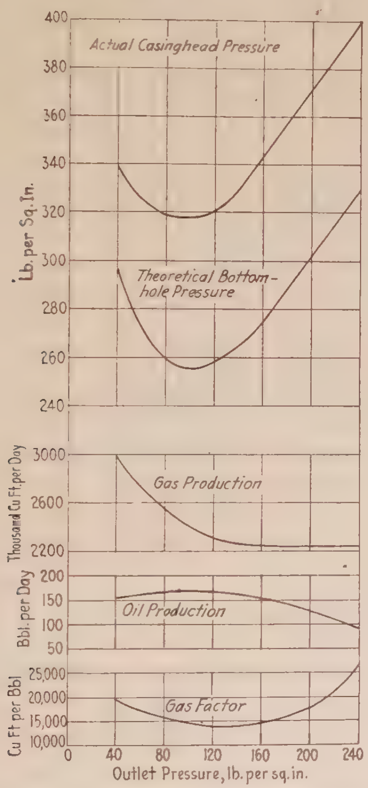

FIG. 13.—ACTUAL BACK-PRESSURE AND CALCULATED PRESSURE TO FLOW GAS ONLY, FROM WELL WITH HIGH GAS FACTOR, THROUGH 2½-IN. TUBING.

slippage and the gas-oil ratio calculated at the absolute pressure in the well outlet. The numerical values of the curves vary with different sizes and depth of tubing, outlet pressures and gravity of gas and oil. From the mass of flow data now being accumulated in the Mid-Continent, empirical curves could be compiled on slippage velocities and pressure drops for the vertical flow of oil-gas mixtures in pipes. Such a set of curves would be of great economic value to the industry, as an aid to lower operating costs and higher oil recovery.

Summary and Conclusions

1. Pressure control does not always necessitate reducing the daily rate of or the deferring of production. Gas energy can be conserved without the cooperation of offset operators, by intelligent control, but more uniform and better results are secured with cooperation.

2. When control is applied during the flush period oil production deferred by pressure control is returned within the early life of the well.

3. The minimum gas factor coincides so closely with the most economic gas factor that in the majority of cases no practical distinction can be made.

4. The design of connections at the top of the well influences the results obtainable. All flow line bends should have the convex side upward.

5. Gas-lift is the most flexible method of pressure control.

6. The suitability of an installed string of flow tubing can be determined accurately by test methods.

7. Tests can be readily conducted to determine the proper pressure adjustments.

8. After a well is properly adjusted few subsequent adjustments are necessary until the method of operation is changed.

9. A well cannot be pinched indiscriminately to any desired rate of production without danger of dissipating gas energy.

10. Water-oil factors may be controlled in the same manner as gas-oil factors.

11. Sand troubles may be alleviated considerably by gas-lift control and water circulation.

12. The relation of outlet back-pressure to bottom-hole pressure is not direct, except in wells with high gas factors and high flow velocities.

13. Working fluid levels control the bottom-hole pressure on wells with low gas factors and low flow velocities.

14. Continuous and steady operation of the average well is thought to be insurance against a short and uneconomical producing life.

Measurements of Original Pressure, Temperature and Gas-oil Ratio in Oil Sands*

By K. C. Sclater† and B. R. Stephenson,‡ Ponca City, Okla.

(Tulsa Meeting, October, 1928)

Recent progress in oil-recovery methods has brought into prominence gas-energy relations in oil sands. The greater the effort made to utilize this gas-energy relationship to the best advantage in oil recovery, the greater becomes the need for more precise information concerning physical conditions as they actually exist in an oil well.

The intelligent use of gas-oil ratios when considering production efficiency has been the subject of much recent discussion. It has been stressed that the pressure as well as the volume of gas must be known when considering the efficiency of a producing well on an energy basis. When methods of production are compared on an energy basis it implies a knowledge of pressure, temperature and physical properties of the fluids at the bottom of the well.

In questions concerning gas-lift and the pressure control of wells usually there is a wide variance of opinion among engineers when energy relations come up for discussion. Perhaps this difference of opinion can be traced to erroneous assumptions made with regard to the physical conditions existing within the well. If erroneous assumptions are made it follows that computations based on these assumptions will give results which also will be in error.

That erroneous assumptions are made is not to be wondered at because when handling a fluid composed of gas and oil, we are dealing with a complexity of hydrocarbon components each varying to some degree in physical and chemical properties. This means that the physical state of the gas and oil will depend not only on temperature and pressure but that it will be influenced also by the relative amounts of the various hydrocarbon components present. If water is present the problem becomes still more complicated.

From these considerations alone it would appear that we can well afford to give some thought to devising more positive methods or means for obtaining data on physical conditions within the well rather than depend entirely on computations from casinghead data. If these data

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† Chief Petroleum Engineer, Marland Production Co.

‡ Physicist; formerly of Research Department, Marland Oil Co.

would tell us definitely how the gas is associated with the oil, in what phase it exists, and what are the relative proportions present in the oil at the face of the oil sand, they would be a decided aid in the solution of all types of oil-recovery problems.

Bottom-hole data have a wider range of usefulness than may at first appear. As used here, bottom-hole data refer specifically to positive measurements of pressure, temperature, gravity of oil, gas-oil ratios, and the physical and chemical nature of the fluid as it exists at the bottom or any other designated point in a well in contradistinction to well data computed from measurements made at the casinghead. A complete set of bottom-hole data obtained immediately the well is "drilled in" would form a basic reference to be used in all subsequent measurements. The type of information these data would furnish is fundamental in character in that original conditions within the reservoir in the vicinity of the well, before depletion of the energy through the well begins, could be determined with a fair degree of accuracy. This information also would be a valuable reference when problems involving well operation and economical methods of oil recovery come up for solution.

Besides serving as a guide in deciding on the best method of producing a well, of equal if not greater importance is the fact that bottom-hole data obtained at subsequent intervals from selected wells in a field, together with good production records, would aid in determining with a greater degree of accuracy, the trend of decline of the field as a whole. A valuable set of records showing the change in gas-energy relations in the oil sand would then be available for making closer determinations of rate of depletion and forecasting ultimate recovery.

Realizing the need for bottom-hole data and their application to the solution of a wide range of oil-recovery problems, some work of a preliminary nature was undertaken by the Marland Oil Co. on devising and developing for field use suitable apparatus which would provide a simple, positive and reliable means for obtaining bottom-hole data, no equipment of this kind suitable for use in an oil well being available on the market. The progress made to date on this problem has not advanced very far beyond the preliminary stage. Equipment has been designed and constructed and some field tests made. The results obtained in these tests, while they do not cover a wide range of conditions, are sufficient, in the interest of stimulating further work along this line, to justify inclusion in this paper.

Field Equipment and Methods for Obtaining Bottom-hole Data

Four pieces of apparatus have been developed for field use, namely, a thief for sampling fluids under pressure, a recording pressure bomb, a maximum pressure bomb and a diaphragm pressure gage. The first three, the thief, recording pressure bomb and maximum pressure bomb

are run together as a test string (Fig. 4) to obtain a complete set of bottom-hole data. Two pressure bombs are run in order to obtain check readings of maximum pressure. The maximum pressure bomb also serves as a sinker.

Thief for Sampling Fluids under Pressure

Important details of the thief are shown in Fig. 1. The steel case forming the main body of the thief is made from heavy 3-in. pipe. Each

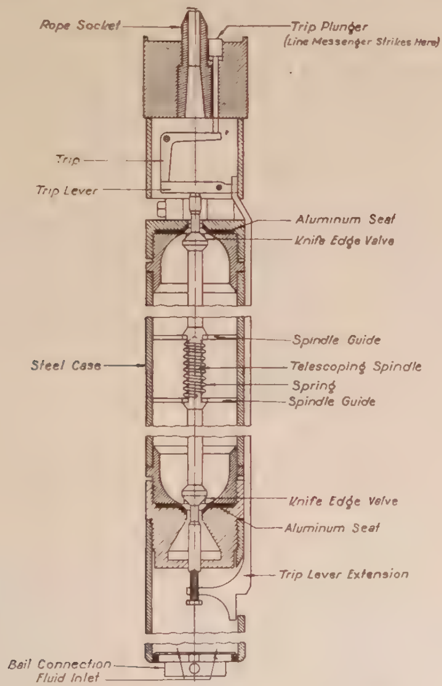

FIG. 1.—THIEF FOR SAMPLING FLUID UNDER PRESSURE IN OIL WELLS.

opening of the sampler, top and bottom, has on its inner edge a special renewable aluminum disk which forms a seat for the steel knife-edge valve. The success of obtaining a good sample under pressure is dependent mainly on a secure seating of the knife-edge valves, hence it is necessary to renew a set of disks for each run. The spindle of the lower knife-edge valve slides within the spindle of the upper knife-edge valve. A heavy steel spring is mounted on the knife-edge valve spindles. Both spindles have an outward extension to provide for the operation of the trip mechanism. The trip mechanism consists of the trip plunger, trip, trip lever and trip lever extension as shown. A maximum thermometer is placed in the space below the lower inlet to the sampler. A connection is also provided for attaching a pressure gage and for drawing off the

contents of the thief for analysis. The capacity of the thief is approximately 3½ liters.

Before the thief is run in the well the spring is compressed and the trip set to hold the knife-edge valves off their seats. This permits passage of the fluids through the sampler as it is lowered into the well. The sampler is run on a sand line to the point in the well where the sample is to be taken and left there for 20 to 30 min. or longer depending upon whether or not it is desired to let the pressure build up in the well. A messenger, consisting of a short length of small pipe, is then released at the casinghead and despatched down on the sand line. The messenger strikes the trip plunger and releases the trip, allowing the knife-edge valves to seat. A sample of the fluid or fluids under the existing pressure is thus obtained. The thief is about 3½ in. dia. by 5 ft. long.

Recording Pressure Bomb

The recording pressure bomb[1] consists essentially of a pressure element, clock and recording apparatus. These are enclosed in a steel

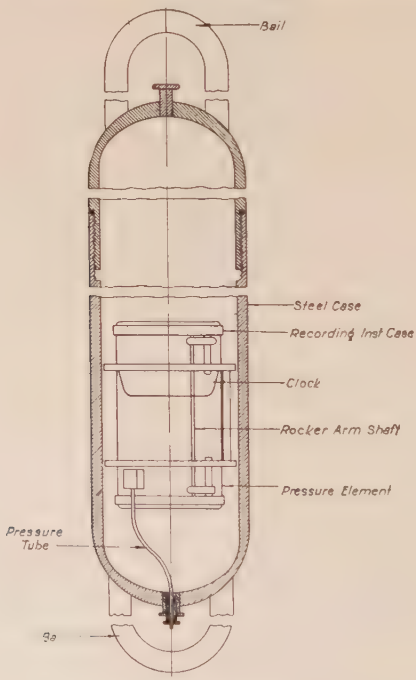

FIG. 2.—RECORDING PRESSURE BOMB FOR OIL WELLS.

gas-tight case as shown in Fig. 2. The pressure element is open to the well pressure through the pressure tube as shown, the latter being securely packed off where it passes through the wall of the steel case to

[1] Designed and constructed by J. E. Shobe, Marland Oil Co.

insure against pressure building up inside the bomb. This piece of apparatus is of very recent development and has proved the most successful for taking pressure measurements in a flowing well. A pressure element for any desired pressure may be installed. Similarly a clock and recording movement for any desired speed may be installed. A circular chart about $2\frac{1}{4}$ in. dia. is used. The bomb is about 4 in. dia. by 3 ft. long.

Maximum Pressure Bomb

Fig. 3 shows a simple maximum pressure bomb. Varied types of construction have been and are in use. The maximum pressure bomb is simply a gas-tight steel case, enclosing one or more maximum reading pressure gages. It is common to use a gage or gages with smoked dials to record the maximum reading. Greater success has been had with this type than with types using a maximum hand or pointer. For obtaining bottom-hole pressures only, the maximum pressure bomb run alone has proved very successful. The

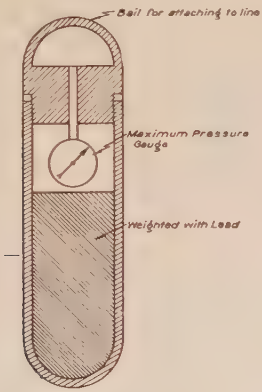

FIG. 3.—MAXIMUM PRESSURE BOMB FOR OIL WELLS.

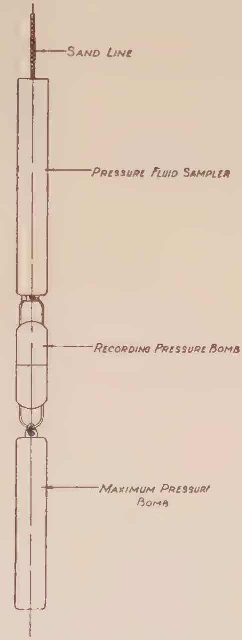

FIG. 4.—FLUID AND PRESSURE TEST STRING FOR OIL WELLS.

dimensions of the bomb used in the test string (Fig. 4) are $3\frac{1}{2}$ in. dia. by 4 ft. long.

Diaphragm Pressure Gage

Fig. 5 shows the diaphragm pressure gage. It is simply a metal diaphragm the top side of which is open to a pressure chamber and tank and the bottom to the well pressure. The gage is designed to run in a well either through tubing or casing. It is run on small size ($\frac{3}{8}$-in.) pipe. This pipe forms the pressure chamber and is connected directly

to the pressure tank as shown in Fig. 5. When the diaphragm is lowered to the desired point in the well, gas or air from the pressure tank is fed into the pressure chamber until the pressure on the upper side of the diaphragm balances the well pressure on the under side of the diaphragm. When balance is reached the contact between conductor and diaphragm (see Fig. 5) is broken and a reading on the pressure gage is taken at the instant the galvanometer needle is deflected. Pressure readings are corrected for the weight of the gas column in the pressure chamber. When installed the small pipe which forms the pressure chamber is packed off at the casinghead.

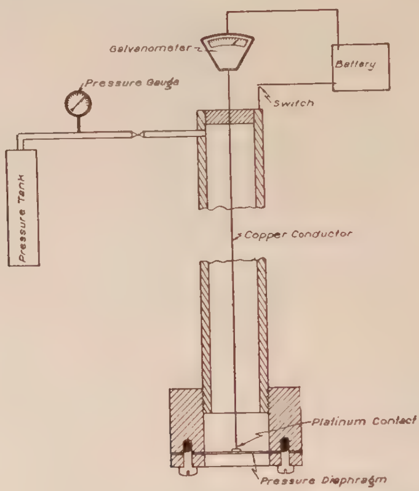

FIG. 5.—DIAPHRAGM PRESSURE GAGE FOR OIL WELLS.

The purpose of this gage is somewhat different from the other pressure gages described. It was designed primarily for obtaining pressures at any point in a well while the well is producing. The pressure on the underside of the diaphragm is indicated at the surface. Inherent defects arising from the design have not yet been fully overcome, consequently consistently successful results have not attended its use. The design and development of a suitable type gage to give continuous readings, observable at the casinghead, of pressures existing in the bottom or any desired point in a well while the well is in operation, deserves the attention of everyone interested in more efficient methods of handling producing wells. Based upon what has already been accomplished in experimental field work in developing a gage of this type, there is every reason to believe that the day is not far distant when such a gage will be available. There are instruments for taking precise measurements being used in other lines of industry which, with some modification, might be adapted for use in well measurements.

Difficulties Encountered in Bottom-hole Measurements

As might be expected, difficulties encountered in obtaining bottom-hole data are due mainly to the limitations imposed by well conditions. These conditions are mechanical and physical. The size of well casing or tubing prescribes the allowable cross-sectional dimensions of the apparatus. Probably this one factor more than any other has retarded development of apparatus for making measurements in wells. No limitations however are put on longitudinal dimensions and this gives some leeway in design. If facilities of good surface well equipment are not available minor difficulties in handling the apparatus arise. Too great a variation in speed, or too sudden braking, when running in or pulling out test apparatus will result in damage to thermometers, gages and recording equipment. Thermometer threads may be knocked down or gage hands jerked out of position or off the pin entirely. If a well is flowing under high pressure it necessitates the use of a lubricator to enter test apparatus in the well. The velocity of flow may be so great that the test apparatus can be lowered only by shutting the well in. Surging or heading conditions in the well may result in false readings of pressure temperature and gas-oil ratio.

Bottom-hole Data—Uses and Applications

Earlier in this discussion attention was called to the fundamental character of bottom-hole data obtained immediately a well is "drilled in." For instance, if it is the discovery well in a field, pressure, temperature and gas-oil ratio measurements taken at the face of the oil sand with the well closed in will closely approximate original conditions within the reservoir. In the absence of definite information pertaining to bottom-hole conditions we are confronted at the outset with the problem of determining, by casinghead data only, the physical conditions existing at the base of a 3000 or 4000-ft. well. Great progress has been made in interpretation of underground conditions through a close study and analysis of casinghead data, but even so, our conceptions of the existing physical conditions do not always accord with facts. In a flowing well do we know how a change in casinghead pressure affects the bottom-hole pressure; how the pressure varies in the fluid column in the well; what is the change in temperature and gravity of the oil, gas and gas-oil ratio from the face of the oil sand to the casinghead? An immediate and definite answer to these questions is very pertinent in deciding questions of well operation. It is not the purpose of this paper to go into a detailed discussion of these data but rather to outline briefly the possibilities of their use and application to oil-field problems. Today, the research engineer engaged in problems pertaining to increased recovery from oil sands is looking to the engineer engaged in active oil-field operations for

information which will assist him in substantiating conclusions and correlating and comparing laboratory results with those obtained under actual field operating conditions. Cooperation of this kind between the laboratory and the field will make for real progress and help eliminate the guesswork in seeking for a solution of oil-recovery problems.

Fig. 6 shows the relation between bottom-hole and casinghead pressure in a well. The bottom-hole pressures were obtained with the diaphragm gage shown in Fig. 5. The exact total depth of the well is 3826 ft. and it is producing from the Chat. It is a small producer with a very high gas-oil ratio. This is the type curve that might be expected in a well producing small amounts of oil with a high gas-oil ratio. It will be noted that for the first 6 hr. the well was closed in there was

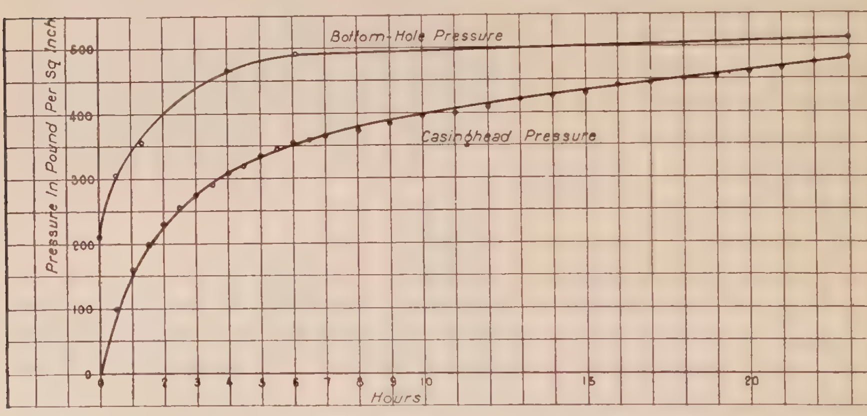

FIG. 6.—CASINGHEAD AND BOTTOM-HOLE PRESSURE TAKEN IN 3800-FT. WELL.

practically no change in the pressure differential between the bottom-hole and casinghead, after this period, however, the pressure differential decreased uniformly, the bottom-hole pressure remained about constant and the increase in casinghead pressure was very gradual following along an almost straight line. Thief samples taken on this well showed inconsistent results because of gas breaking through the oil column at the bottom of the hole when the thief was run. The most successful test made showed a gas-oil ratio of 178 cu. ft. at the bottom of the hole. No gas-oil ratio was obtainable simultaneously at the casinghead. There was a variation in gravity from 42° to 40.6° A. P. I. between the oil at bottom-hole and casinghead. The average bottom-hole temperature recorded was 127° F.

In a well having a high rate of oil production and low gas factor it is to be expected that the pressure differential between the bottom of the hole and the casinghead would be greater. It may be possible from a

study of curves showing relationship between casinghead and bottom-hole pressure to determine the capacity and rate at which a well is capable of producing.

In Table 1 are presented bottom-hole data obtained in a flowing well producing from the Wilcox sand. The differences between bottom-hole and casinghead data are very pronounced. A large increase in gas-oil ratio with a decrease in temperature, gravity of oil and gravity of gas is noted.

TABLE 1.—*Bottom-hole Data for a Flowing Well*

[See Fig. 7 for pressure curves.]

Daily Oil Production, 300 bbl. Daily Gas Production, 375 M. cu. ft.
Total Depth, 3389 ft. Size Flow String, 5$\frac{3}{16}$-in. Casing
Producing Formation, Wilcox Sand.

	Bottom-Hole	Casinghead
Pressure, lb	325	50
Oil and Gas, Deg. F	124	82
Gas-oil Ratio, cu. ft. per bbl	488	1250
Gravity of Oil, Deg. A. P. I.	41.2	41.0
Gravity of Gas	0.994	0.963

	Oil Analysis, Deg. A. P. I.	Yield, Per Cent.
Gasoline	60.1	35.3
Kerosene	43.1	20.0
Gas Oil	36.1	11.8
Light Lubricating Distillate	31.9	8.8
Medium Lubricating Distillate	29.2	6.0
Residuum Gravity	20.8	

	Per Cent.
CH_2	5.3
C_2H_6	69.8
N_2	24.4
CO_2	0.3
O_2	0.2
B.t.u., per cu. ft	1285

The effect of the higher pressure at the face of the sand is observed in the richer gas and higher gravity of oil in the bottom-hole sample. The amount of gas in the liquid phase is greater at higher than at lower pressures, also as the pressure is lowered the amount of gas in the liquid phase is decreased and the amount in the gaseous phase increased. Surface tension and viscosity are also lowered as the quantity of gas in the liquid phase is increased, hence it is desirable to maintain as small a pressure differential as operating conditions will permit at the face of the sand. With bottom-hole data before him, the engineer can better visualize the probable effects of changes in well operation.

The results of a test made with the recording pressure bomb to determine the pressure at various points in the well from which bottom-

hole data in Table 1 were obtained while the well was flowing are shown in Fig. 7. Between 500 and 1000 ft. there is an abrupt change in pressure. This evidence indicates that a flowing well can have a fluid level. Further experimental work and tests in the field probably will show that the average flowing well has a fluid level. A relation may and probably does exist between the chemical composition and physical characteristics of the oil and gas and the pressure and temperature at which the abrupt

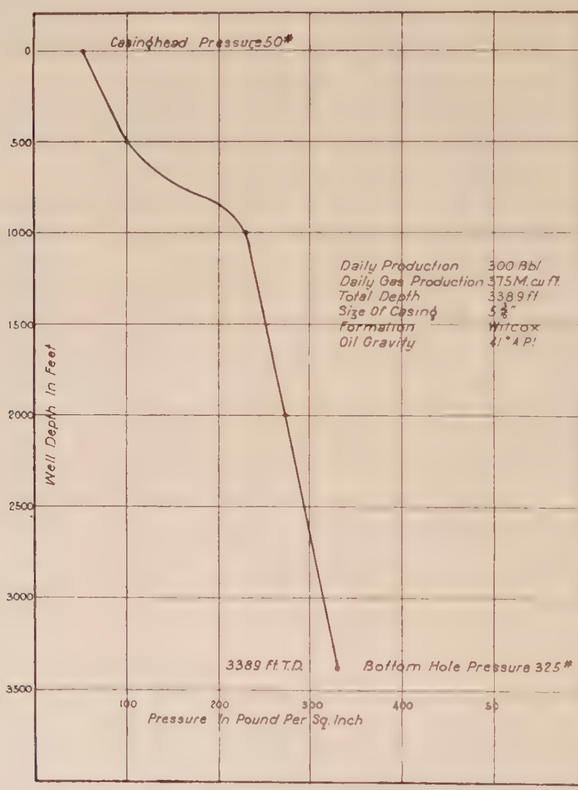

FIG. 7.—PRESSURE CURVE IN FLOWING WELL.

change occurs. From the bottom of the hole to the point where the abrupt change in pressure occurs, the oil is lifted chiefly by levitation due to gas in solution in the oil expanding, above this point the oil is carried upward in a fine spray by the velocity of the gas.

If, in addition to pressure readings, corresponding temperatures are taken we have a reliable and practical means of acquiring valuable information on velocities in the flow string of an oil well. This information would be vital in the design of flow strings since at present there is no means for computing frictional effects of gas-oil-water mixtures. If

the evidence presented by the curve shown in Fig. 7 is correct, it points to the fallacy of assuming that the velocity in the flow string of the average oil well is a smooth or straight-line function of the depth.

By taking measurements of bottom-hole pressure at intervals with the well bailed down, and observing the rate of inflow with the well closed in, the condition of the well can be checked and operating information furnished as to whether or not a well requires cleaning out. Bottom-hole data obtained before and after a well is shot will assist in appraising the results of shooting. Any changes in pressure, temperature, characteristics of oil, and gas-oil ratios can be detected at once by an examination of the information furnished by the bottom-hole data obtained before and after the shot.

In repressuring operations the use of bottom-hole pressure may be used to follow the pressure trends underground. Where repressuring operations are contemplated, bottom-hole pressures taken at various points in a field facilitate the interpretation of sand conditions. In the selection of key wells it is important to have reliable data on reservoir pressures and sand conditions.

A close study of bottom-hole pressure data in a relatively new field in Texas before repressuring operations were started revealed a pronounced pressure gradient between the high part of the structure and the edges of the field. The upper part of the structure contained gas only and large volumes were produced in an effort to produce oil. So rapidly was the gas produced from the top of the structure that it resulted in reducing the pressure in the gas area to below that existing in the edge wells of the field, thus establishing a pronounced pressure gradient. A series of bottom-hole pressure tests brought out this fact very clearly.

In the interpretation of underground structure and sand conditions bottom-hole data have a very definite application. Correlation of producing sands is possible by comparing pressure, temperature, gas-oil ratio and composition of the fluid content measured at the face of the oil sand. In this connection, attention is drawn to the bottom-hole data in Table 2. It will be noted that the A. P. I. gravity of the bottom-hole sample with well closed is less than the sample taken at the casing-head while the well was flowing. The sample with the well closed in was first to be taken, the other was obtained the day following. This difference in gravity is accounted for by the fact that the well is producing from two distinct horizons, namely, the Wilcox Sand and the Siliceous Lime. When the well was drilled into the Wilcox Sand the gravity of the oil was 37° A. P. I. Later when the well was deepened to the Siliceous Lime the gravity was observed to be about 33° A. P. I.

Pressure irregularities at the face of a sand over the field may provide a clue to changes in sand conditions. An area where cementation or sedimentation has altered the permeability of the sand to any extent

TABLE 2.—*Bottom-hole Data*

Well pinched to 50 bbl. daily; average gas-oil ratio 550 cu. ft. per bbl.
Total depth, 2899 ft. Size flow string, 6⅝-in. casing.
Producing formations, Wilcox Sand and Siliceous Lime.

	Well Flowing		Well Closed In	
	Bottom Hole	Casinghead	Bottom Hole	Casinghead
Pressure, lb	310	10 to 25	725	160 to 480
Oil and Gas, Deg. F	127	86	126	
Gas-oil Ratio, cu. ft. per bbl	214	550	231	
Gravity of Oil, Deg. A. P. I.	36.7	36.1	35.9	
Gravity of Gas	1.089		1.117	

Oil Analysis Bottom-hole Sample

	Well Flowing		Well Closed in	
	Gravity, Deg. A. P. I.	Yield, Per Cent.	Gravity, Deg. A. P. I.	Yield, Per Cent.
Gasoline	56.5	22.7	56.4	24.0
Kerosene	37.7	16.0	37.7	16.7
Gas Oil	31.9	11.7	32.5	10.4
Light Lubricating Distillate	30.0	11.5	29.5	11.0
Medium Lubricating Distillate	28.0	6.7	28.0	7.0
Residuum	21.3	31.4	22.5	30.2

Gas Analysis Bottom-hole Sample

	Well Flowing, Per Cent.	Well Closed in, Per Cent.
CH_4	20.0	20.7
C_2H_6	53.0	55.0
N_2	13.6	11.0
CO_2	0.2	0.2
O_2	0.2	0.1
C_3H_8	8.0	8.0
C_4H_{10}	5.0	5.0
B.t.u., per cu. ft.	1503	1543

would be reflected in the bottom-hole pressure of producing wells in that area.

In problems relating to rate of decline or rate of depletion, we are confronted with the problem of determining only from the amounts of gas and oil produced, how the rate of decline is trending. From this information it is usual to project into the future, curves which will assist in forecasting the expected ultimate recovery. If the amount of gas and oil produced from a reservoir is known, and also the composition

of the gas and the oil, production data may further be supplemented by bottom-hole pressure and temperature readings at regular intervals. Pressure volume relations can supplement statistical data in forecasting ultimate recovery and rate of depletion.

The use of bottom-hole data may be extended to problems of proration; also to problems involving equity where working agreements are in force. The purpose of any proration agreement is to reconcile equities in a field. Since the amount of oil recovered is controlled by the amount of energy in the reservoir, it follows that methods of proration should be based on energy considerations. Complete bottom-hole data gathered at regular intervals will be of assistance in determining the amount of proration that each well receives. It may be that when sufficient progress has been made in taking bottom-hole data, equitable methods of proration based on reservoir energy will suggest themselves.

Summary

In this paper attention is drawn to the need for more precise information regarding physical conditions at the bottom of oil wells. It is suggested that simple, positive, reliable means can be developed for obtaining this information. Preliminary work has already been done on this problem, and the apparatus designed and developed, together with the methods of using, are briefly outlined. From a study of the results obtained thus far on the subject of bottom-hole data, it is concluded that:

1. It is feasible to develop suitable apparatus which will provide a simple, positive, reliable means of obtaining bottom-hole data, such data consisting of positive bottom-hole measurements of pressure, temperature, gas-oil ratio, and the composition and physical properties of the gas and oil in the well.

2. Information furnished by bottom-hole data is fundamental in character, and warrants the consideration of everyone interested in promoting more efficient methods of oil recovery.

3. Bottom-hole data, systematically gathered and correlated, can be put to immediate practical use in the field.

4. Measurements made at the casinghead are, used alone, inadequate for the proper interpretation of bottom-hole conditions.

5. Further study of bottom-hole data should be a valuable aid in the analysis of well troubles and be the means of removing misconceptions regarding flowing conditions in an oil well.

With our lack of knowledge regarding the frictional effects of gas-oil-water mixtures, either in the sand or in the flow column of the well, any reliable information that can be obtained in the field to supplement laboratory data must not be overlooked. Bottom-hole data obtained at the beginning of the life of the field, and at intervals thereafter, are a valuable source of such reliable information.

DISCUSSION

E. O. Bennett,* Ponca City, Okla.—We all know that gas deviates from Boyle's law, and if we know the original pressure and volume in the well, we can correct for the deviation, which will not be known if the gas is measured from the volume taken at the surface; for example, if the gas showed 300 lb. pressure in the well and was expanded to atmospheric pressure, it would probably deviate in some cases as much as 20 per cent. from Boyle's law. If this same gas were measured at low pressure from the well head without taking a sample from the bottom of the well to determine the volume which it occupied in the well and to determine the amount in solution in the oil, there is no way in which the deviation could be ascertained. In any producing formation there may be as high as 20 to 30 per cent. more gas than estimated to start with. If you do not know what it is in the formation, you can never control it from the surface in order to utilize the extra energy it contains. In other words, we are striving to utilize a smaller amount of energy per barrel of oil produced, and by doing so we will get our production at a lesser cost.

If you are drilling through two or three pay sands in the same well, the bomb provides a way by which you may have a check during the life of the well on what percentage of oil is coming from each different and separate formation.

A sample can be obtained from the first pay with the original amount of gas in it. The same can be done for other pays, and by a definite knowledge of the comparison of these gases, the amount of oil coming from each pay can be closely approximated.

Specific use of this apparatus was made in the Yates pool in Texas. When this pool was first drilled in, the hydrostatic pressure was greater than the corresponding well depth. This is a field in which approximately all of the oil will be produced without pumping. It was a general opinion of the operators in the field that the pressure in the formation was 500 lb., this being deduced from gage pressures at the well tops. Calculations of volume of both oil and gas showed that the pressure should be 710 lb. and actual check with the bomb showed the pressure 705 lb. From this it is easily seen that there is approximately 50 per cent. more energy in the gas than was anticipated.

If you dissipate the gas faster than you should, you are wasting more energy than is required. The use of the bomb tells you what control to put on the well to get the greatest recovery. We all agree that a certain amount of back-pressure on a well is beneficial but to determine just what back-pressure to apply is a problem. If the well will make 10,000 bbl. and you cut it down to 5000, that may not be the right point. The proper way to operate the well is to get a reasonable amount of oil with a minimum amount of energy per barrel. If we can operate it at 2000 bbl. and use less energy per barrel at that point, then at 8000 bbl. the well would give a greater recovery and would not decline as fast as if you were producing it wide open. Where the working pressure in the bottom of the hole is approximately 90 per cent. of the bottom-hole shut-in pressure, it seems to be approximately the economic point; that is, operating conditions that give the greatest amount of oil with the least amount of gas per barrel.

The bomb is being successfully used also in a field where repressuring is taking place. To get the best results in repressuring in this field, the operators take all the available energy and return it to the formation for the maintenance of production. In a case like this it is extremely desirable that the pressure gradient across the field be zero; in other words, that the pressure be kept uniform throughout the entire field. This can be done in two ways—one is to use the input pressure well. Here we record the pressure in the well with a recording gage at the well head and allow the gage to run until the clock traces a cycle. This gives a rock pressure very closely. Volumes of gas are then so regulated that the pressures are kept uniform. Where there

* Chief Engineer, Marland Companies.

are but a few input wells and a large number of gas wells, the bomb is run in to record the pressure in the formation.

In Texas, two major offsetting companies have agreed to keep the pressures constant, regardless of production. If the pressure is kept constant there will be no migration of oil across property lines.

C. V. MILLIKAN,* Tulsa, Okla.—The advantages which might be gained by obtaining bottom-hole pressures have been realized only during the past year or so. In many places the rock pressure has been considered equal to the static head of the fluid. In the case of water without gas this is probably correct but for oil with associated gas the density varies so greatly that the static pressure cannot be calculated. In deep wells I have seen the bailer go through 200 or 300 ft. of oil and then through a gas pocket several hundred feet before again striking fluid.

It will be but a short time until an instrument is developed which will take continuous readings and will be small enough in diameter to be run inside of 2-in. tubing. If it is larger in diameter it cannot be used in wells with 2-in. tubing and in larger diameter holes may obstruct the flow sufficiently to give erroneous results. The length may be practically unlimited, although the shorter it is the more easily it may be handled. Certainly we are handicapped toward advancement in design of flow strings for natural flowing or gas-lift wells without an instrument to record bottom-hole pressures under normal operating conditions.

E. O. BENNETT.—The instrument Mr. Sclater was talking about was made with an alarm clock and pressure gage. At the top is a test pressure gage and the bottom is a little clock. The chart is turned on the face of the clock. In order to hitch the two together we put one above the other and put in a connecting link. The pen is actuated by the element at the other end. All the instrument people said it could not be done, yet we have been running one.

C. V. MILLIKAN.—Do you have any difficulty in the vibration affecting the reading?

E. O. BENNETT.—It gives smooth lines on the chart.

K. C. SCLATER.—We had some trouble with the pen plugging. There is little or no vibration.

E. O. BENNETT.—The data taken with this type of instrument explodes the theory that one can calculate the design of tubing for a gas-lift well. When pressure reduces to a certain point below that of the field, at that point gas breaks out and lifts the velocity. Not knowing where the point is, it is impossible to work out theory on a string of tubing for efficiency on a gas-lift well.

H. S. BERKEY,† Huntington Beach, Calif.—I do not know that we have anything on bottom-hole pressures, but we have a tube for getting the fluid level, which is somewhat better than dipping for it and getting an erroneous impression.

We use a 2-in. pump plunger, weld the heads in, with a check valve in the bottom end and a ¼-in. nipple and valve in the top end. This we partly fill with oil and put an air or gas pressure of 25 lb. or more in the plunger. Suitable connections to a sinker and sand line are made and the bomb is lowered to a certain measured depth, which is several hundred feet below the indicated fluid level by oil on the line. The bomb is allowed to stand at this depth for a short period to allow pressure without and within the bomb to equalize. It is then pulled out and a pressure gage connected

* Amerada Petroleum Corpn.
† Standard Oil Co. of California.

to the ¼-in. nipple and valve, the valve opened and the pressure read from the gage. The pressure as read will indicate the amount of fluid above this measured depth by dividing the pressure in pounds by a factor which is slightly changeable with the gravity of the fluid. This method gives approximately true measurements unaffected by gas action. The same tool would take bottom-hole pressures, if run to bottom.

C. V. Millikan.—Would you mind describing for us in more or less detail the method of measuring the gas-oil ratio after bringing the bomb to the surface?

K. C. Sclater.—Pressure was let off gradually and we measured the gas water by displacement. The sample of oil was taken directly off and the bomb closed until the gas pressure was taken. We expect to work this out further in the field on wells coming in and work out a definite method.

C. V. Millikan.—In one of the tables, you mention 400 cu. ft. at the bottom with 1200 at the surface. Did you measure this by water displacement?

K. C. Sclater.—Yes. The sample was under pressure; it was taken up, the pressure read off and casinghead measurements made.

C. B. Williams,* Cisco, Tex.—It is my understanding that the gas-oil ratio coming from the sand is really not so important—where, as we very frequently have found, the cause of the bottom-hole pressure is due to water pressure.

E. O. Bennett.—That point is of just as much importance in that particular case—as the water comes in and holds the pressure up as long as the gas is in solution. If the gas is let off, the water will be brought in sooner than if the gas were kept in solution. The pressure differential rather than the particular amount of gas is driving the oil in the well. It is not so important for that, but serves to hold off the water from the well. In that case gas is a means of keeping up the pressure. However, gas plays a part in a very different way with the water than otherwise.

R. Van A. Mills,† Bartlesville, Okla.—Did they find any difference in the formation gas-oil ratio as measured by using the bombs and the gas-oil ratio obtained by dissolving gas in the oil in the laboratory? I heard some time ago they found more gas in solution in the oil from the formation than they could put back into solution at the same pressure.

E. O. Bennett.—We have not been able to put back the original amount of gas, in the laboratory.

J. F. Dodge,‡ San Francisco, Calif.—Might it not be that the gas in the pressure bomb was not in solution? When you attempt to duplicate the condition you put the gas in simple solution but there was not time enough to allow the gas to go back in occluded form or to be adsorbed on the sand grains as it was originally in the formation.

E. O. Bennett.—That is entirely possible. If you fill a tube three-quarters with oil and one-quarter with gas and let it stand still the pressure will be maintained and there will be very little absorption, but shake the tube and it will drop right down. There is much that is yet to be worked out.

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* The Texas Co.

† Petroleum Engineer, U. S. Bureau of Mines.

‡ Standard Oil Co. of California.

W. V. Vietti,* Ponca City, Okla.—You speak of putting the gas in the oil as it was originally, but you do not know what the original pressure was, unless you took the original rock pressure of the first well drilled before the oil was produced.

We know from measurements that the figures used in the past for rock pressures are wrong by several hundred pounds. In taking the pressures at the bottom of the hole, you are still possibly getting pressures below the pressures in the formation 300 or 400 ft. back from the face of the well bore.

R. Van A. Mills.—I have been attacking this problem from a different point of view. I have tried to work out depth-pressure gradients for different localities, and then calculate the initial pressures in a field according to the best field practice to get the natural pressure record in the depth of the wells. The gas companies are very careful in measuring pressures in their wells. In the State of Oklahoma it is surprising how closely the depth-pressure figures check. Taking the state as a whole—outside of Osage County—we have a depth-pressure gradient of 42.16 lb. for every 100 ft. of depth for wells from 2000 to 3000 ft. deep. These figures check so closely, I believe we can use them to estimate the natural rock pressure at different depths. At depths below 4000 ft. the pressure gradient is 33.49 lb. per 100 ft. of depth.

In Osage County figures are rather regular. In shallow wells less than 2000 ft. deep the gradient is around 37 to 40 lb. to the hundred feet—for wells around 2000 ft. in depth it runs 40 lb. per hundred feet.

So we can use these figures as they apply in districts close to the wells where actual measurements were made.

R. R. Brandenthaler,† Bartlesville, Okla. (written discussion).—This paper is unquestionably one of the most valuable contributions relating to methods of increasing production from oil sands that has been presented during the past few years. It establishes the basis for obtaining fundamental data, which in the past have been based largely on conjecture. The data as outlined in the report can be readily translated and used as a tool in solving a number of production problems. The paper points out that estimates of future recovery can be made with greater accuracy when bottom-hole data are obtained upon initial completion and at subsequent intervals during the productive life of the sand. It also points out that the information gained serves as a guide in determining the best method of producing a well.

The paper is essentially sound and I have no direct criticism to offer as to its practical applicability to the production of oil, but there are several important considerations which I might emphasize. Bottom-hole data are obtained under static conditions and also during flow. Of these, the data under static conditions are fundamental because they form a basis from which to work, or, all changes can be referred back to and compared with them without necessitating the use of assumptions which might be, but usually are not, correct.

At present there is no method known whereby data taken at the well head can be translated in terms of bottom-hole data.

Horizontal-flow formulas either of oil or gas are not applicable because the density of the gas or oil is considered as a constant. Any vertical-flow formula, to be accurate, must take into account changes in density.

Another point of interest is brought out in Fig. 6. The pressure and casinghead pressure at the end of 24 hr. was only about 35 lb. Assuming that the casing were filled entirely with gas, the weight of a column of gas 3800 ft. high, and with a recorded well-head pressure of 480 lb., would weigh approximately 48 lb. With oil present in the well, the pressure against the sand would be greater, hence one would expect

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† Petroleum Engineer, U. S. Bureau of Mines.

a greater difference between the bottom-hole and casinghead pressures than was actually observed.

Another fact brought out in Fig. 6, and indicated by the time required for the pressure to build up at the bottom of the well, was the necessity for allowing sufficient time for the bottom-hole pressure to attain a maximum in order to obtain an accurate measure of the rock pressure, otherwise the tendency would be to base comparisons of bottom-hole data on rock pressures less than the actual. In addition, other factors such as temperature, gas factor and physical properties of the oil will vary with the pressure accepted as the rock pressure.

While bottom-hole data obtained under static conditions are important, it is also evident that the same data obtained during flow are of essential importance to determine the conditions under which the gas energy is utilized to the fullest extent. Obviously, it would be impossible to obtain bottom-hole samples of the fluid during flow. However, having available the pressures and temperatures, also the bottom-hole data determined under static conditions, it would be possible to calculate, within reasonable limits, the gas factor, viscosity and other characteristics of the oil at the bottom of the well.

Repressuring during Early Stages of Development

By C. E. Beecher,* Bartlesville, Okla.

(Tulsa Meeting, October, 1928)

The application of gas or air under pressure to obtain more oil from a sand which has been practically exhausted by ordinary production methods has been practiced to a limited extent for many years. Until recently such methods were confined to the Eastern fields, principally those of Ohio and West Virginia, where in many cases the production obtained after applying pressure for a few years was nearly equal to the total production prior to that time which had been obtained by the usual production methods. As early as 1917, J. O. Lewis[1] called attention to this method of increasing the recovery of oil and cited the phenomenal results obtained by H. E. Smith, I. L. Dunn and O. C. Dunn, who pioneered the application of air or gas pressure recovery methods. With this information available it would appear that other oil-producing sections of the country have been extremely slow to realize the advantages of repressuring. However, after a few successful projects in the Mid-Continent area, the oil producers appreciated the value of this method for obtaining further and profitable production from their practically exhausted leases and are now making extensive use of it.

In general, it has been the practice to apply pressure to the sands when production has declined to a small yield per well. The purpose of this paper is to discuss some of the advantages which may be expected from returning gas under pressure to the oil sands during the early stages of development, before the rock pressure has been dissipated and the gas exhausted, and to stimulate discussion of this subject on which comparatively little actual field data are available.

The Function of Gas

Gas associated with or dissolved in the oil is the source of energy causing movement of the oil to the well. When this energy is dissipated production ceases. The exception to this general statement is found in fields where hydrostatic water pressure may supply energy after the gas

* Chief Production Engineer, Empire Oil & Refining Co.

[1] J. O. Lewis: Methods for Increasing the Recovery from Oil Sands. U. S. Bur. Mines *Bull.* 148 (1917).

is exhausted, in the form of edge water or in fields where practically no gas exists and water alone is the propelling force.

Gas under pressure dissolves readily in oil, following approximately Henry's law,[2] that is, the volume of gas dissolved increases with the pressure. The physical properties of oil, such as viscosity[3] and surface tension[4] are changed by the amount of gas in the solution. At comparatively low pressures sufficient gas will dissolve in oil to produce an effective decrease in both the viscosity and surface tension.

The flow of any liquid through a capillary tube is inversely proportional to its viscosity and directly proportional to the pressure difference, other conditions being constant. Many openings within the average oil producing sand are of capillary dimensions although not constant in size and shape. It seems reasonable to assume that the laws governing capillary flow would apply to the movement of oil through the sands, assuming that both the oil and gas are in a liquid state.

A difference in pressure must exist for flow to take place, yet any drop in pressure will liberate gas from solution in the oil, causing the oil to become more viscous and thus set up resistance requiring a greater pressure differential to produce flow. The liberated gas exists as small bubbles dispersed through the oil or as free gas. In the former state conditions would be favorable for increasing the resistance to flow due to the formation of alternate layers of gas and oil in the capillary openings through which the fluids must pass. The resistance results from the force necessary to deform and move the gas bubbles through the capillary openings. This is commonly referred to as the "Jamin effect." To what extent this phenomenon actually exists within an oil sand we do not know; however, laboratory experiments[5] indicate that under favorable conditions such resistance may be of great magnitude.

The surface tension of an oil in a gas-oil reservoir is affected by pressure the same as viscosity, *i. e.*, as the gas is exhausted and the pressure decreases the surface tension increases. A large percentage of the oil remaining in the sands must be held there by capillary action. When gravity is the only force opposing capillarity, little or no additional recovery can be expected.

It is apparent that gas is the most important factor, effecting the recovery of oil by its propulsive and expansive force and by changing

[2] A given quantity of liquid will dissolve at constant temperature quantities (by weight) of the gas which are proportional to the pressure of the gas.

[3] D. B. Dow and L. P. Calkin: Solubility and Effects of Natural Gas and Air in Crude Oils. U. S. Bur. of Mines *Repts. of Investigations*, Ser. No. 2732 (Feb., 1926).

[4] C. E. Beecher and I. P. Parkhurst: Effect of Dissolved Gas upon the Viscosity and Surface Tension of Crude Oil. Petroleum Development and Technology in 1926, A. I. M. E. 51.

[5] F. G. Tickell: The Function of Natural Gas in the Oil Sand. *Oil Field Engineering* (March 1, 1928) 11.

the physical properties of the oil, such as, viscosity and surface tension. The benefits derived from the physical changes are reduced as the period of production increases and the pressure decreases. At some time during the producing life of a well, gas may actually retard the flow of oil because of the formation of bubble resistance. Thus it appears that gas plays a dual part in the recovery of oil, depending largely upon pressure conditions.

Any method for increasing the amount of oil recovered from the sand should of necessity take into consideration means for better utilization of the potential energy possessed by the gas. The amount of this energy available for doing work cannot be calculated in foot-pounds but the energy required to produce a given unit of oil can be closely approximated if the pressure and volume of gas produced with the oil are known. The gas-oil ratio is, therefore, an indication of the efficiency of production if pressure is taken into consideration.

Advantages of Returning Gas to the Sand

The energy available for moving oil is limited by the pressure and volume of gas originally associated with the oil. This energy is rapidly dissipated by the usual production methods without doing a maximum amount of effective work in moving oil to the well. A high initial production with a rapid decline constitutes the production history of the average well and the average oil field. It is hardly necessary to mention the evils resulting from these periods of peak production and to point out the advantages of a more uniform rate of production.

A more or less uniform and sustained rate of production can be anticipated by controlling the rate at which the available energy is dissipated per unit of oil produced and by supplying energy from some other source.

Field experiments on individual wells have demonstrated in some instances that the rate of decline can be checked and a greater ultimate recovery obtained by holding pressures on the well to control the amount of gas produced with the oil. Control of this type to be most effective should start with the initial production of the well. The controlled production will be less for a short period of time than could be obtained with the well flowing uncontrolled, but the rate of decline will be much less and the total production will soon be in excess of that obtained for a corresponding period of open flow.

A portion of the energy dissipated in producing the oil can be restored by returning gas under pressure to the sand before the rock pressure has been lowered materially. Under these conditions a maximum amount of work should be obtained from the returned gas because the oil is less viscous due to the gas in solution and will move through the

sand with less resistance, also, the sand is saturated with oil which will prevent by-passing of the gas through drained parts of the sand, which frequently occurs when applying pressure to an exhausted field. The point of applying pressure should be some distance from producing wells and thus effect the movement of a large portion of oil which is usually retained in the sand because of insufficient gas to carry it to the well.

By a combination of controlling the gas-oil ratio and repressuring, a higher rock pressure will be maintained in the vicinity of the well which should help to reduce the bubble resistance or "Jamin effect" resulting from an excess volume of free gas.

Edge water encroaches as the gas is exhausted and the pressure decreases. A sustained pressure in the sand resulting from repressuring should not only retard the encroachment of edge water but should also make possible the recovery of a portion of the oil that would be isolated or entrapped by the water.

Because of the additional energy supplied by early repressuring less wells will be required.

Repressuring offers a means for conserving much of the gas which is frequently wasted during the flush period of production. The gas thus conserved serves a double purpose, it aids in increasing the amount of oil and gasoline recovered, and will be available again in the form of gas for repressuring and for lease operation. Under such conditions the gas supply will be sustained or at least available for a much longer period.

There is a time in the life of many wells when they cease to flow or the flowing production has declined to such a point that it is necessary to resort to the gas-lift or pumping. This can be extended many months as a result of repressuring. By observing the gas-oil ratio a period may then be reached when better efficiencies can be had with the gas-lift. After this method of producing ceases to be efficient better results will be obtained by pumping. Through all the stages it is essential that careful attention be given to the gas-oil ratios to determine the efficiency with which the oil is being recovered. Because of the sustained pressures the fluid levels will be high and the gas-lift operation more efficient. The same should hold true for production obtained by pumping.

In the Dominguez field, California, where repressuring operations have been in progress for about two years, many wells that were produced by the gas-lift at the time repressuring started are now flowing naturally.

The operations of the Marland Oil Co. of California[6] in the Seal Beach field, where repressuring is carried on under a pressure of approximately 1500 lb., indicate that such operations increase the production of

[6] A. H. Bell: Recent Developments in Gas-lift Methods in California Oil Fields. Petroleum Development and Technology in 1927, A. I. M. E., 136; Summary of Repressuring Experiments in California Fields, *Loc. cit.*, 299.

wells on the gas-lift, move oil that would otherwise be left in the sand, and hold back edge water.

Production in the Turberville pool,[7] Archer County, Texas, the Cook pool, Shackelford County, Texas, and the Blake pool, Brown County, Texas, has been substantially increased as a result of repressuring during the early life of the field. A large percentage of gas produced is returned to the sand and by careful observation of the gas-oil ratio for individual wells an effort is made to obtain the maximum energy from the gas. With the exception of a few wells, production is obtained entirely by pumping. These are low-pressure fields, the gas injection pressures varying from 27 to 300 lb. per square inch.

One operator in the Cook pool is drilling wells several locations ahead of present producing wells, for the purpose of returning to the sand residue gas that is now going to waste. This gas is in excess of that required to repressure the present producing area. An earnest effort is being made by the operators in this pool to conserve every cubic foot of gas.

Pressures

The rock pressure in a virgin field may be only a few pounds or many hundred pounds per square inch, depending largely on the depth of the producing sand. In the case of high pressures it is natural to ask if it is economical or practical to return the gas to the sand. Sufficient information is not yet available to answer this question in detail, however, as previously mentioned, pressures up to 1500 lb. per sq. in. have been successfully used.

High pressures are practical from a mechanical standpoint. Compressor manufacturers are building special units for discharge pressures as high as 15,000 lb. per sq. in. and units ranging from 50 to 1500 hp. for discharge pressures up to 1500 lb. per sq. in. are practical. Where high pressures are required for repressuring it is likely that the wells will be produced against a high back-pressure which will permit delivering gas under pressure to the suction of the compressors and thereby reduce the horsepower required to deliver the gas at a high pressure. For example, assuming an intake pressure of 20 lb. and a discharge of 1500 lb., it will require 150 hp. to deliver approximately 570,000 cu. ft. per day by 3-stage compression. With an intake pressure of 75 lb. the same 150 hp. would deliver approximately 900,000 cu. ft. of gas per day against 1500 lb. discharge pressure.

It is well known that the gasoline content of natural gas decreases as the back-pressure on a well increases. Regardless of the back-pressure there will be some gasoline produced during the process of compressing

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[7] E. V. Foran: Effect of Repressuring Producing Sands during the Flush Stage of Production. Petroleum Development and Technology in 1927. A. I. M. E., 285.

and cooling which will be necessary to attain high discharge pressures. Where large volumes under high pressure are required for repressuring it might be practical to install a large-capacity, low-pressure plant for extracting the gasoline. The discharge from this plant could be sufficiently high so that two more compressions would be required to deliver the gas under sufficient pressure to force it into the oil sand.

Some knowledge of the pressure required to return gas to the sand can be obtained by using a device that will record the actual pressure at the face of the oil sand. The pressure necessary actually to force the gas into the sand will be in excess of that found at the bottom of the well. While obtaining data on the rock pressure it would be advisable to ascertain the temperature and to obtain a sample of the oil under pressure from which can be determined the amount of gas in solution.

The percentage of oil recovered from deep sands under high pressures is usually greater than for shallower sands with lower rock pressures. This greater recovery is probably due to more energy in the gas and to changes in the physical properties of the oil, such as viscosity and surface tension, resulting from the higher pressures. In general, the favorable results obtained from repressuring practically exhausted shallow sands cannot be expected when applied to deeper sands. If a greater recovery is to be obtained from the deeper sands it, therefore, seems advisable to start repressuring during the early stages of development, when results can be obtained with a smaller volume of gas.

For producing sands found at comparatively shallow depths with rock pressures of 500 lb. or less the problem of repressuring is comparatively simple compared to high-pressure operations requiring expensive machinery and equipment as well as great care in handling. In general, shallow sands have responded well to the air or gas drive after production has been exhausted by other methods. This is probably due to the lack of sufficient gas originally with the oil, together with its inefficient use, which has resulted in leaving a large percentage of the oil in the sand. If repressuring operations are started as the field is developed more oil will be recovered in less time than by present methods. For example, assume that 20 per cent. of the oil is recovered by normal methods in 8 years, following which 10 per cent. more is recovered by the air drive during the next 6 years, making a total of 30 per cent. in 14 years. Now, if the gas produced with the oil had been returned to the sand systematically beginning with the development of the field it is estimated that 30 per cent. of the oil could be recovered in 8 years or less, instead of 14 years.

Use of Dry and Wet Gas

Where high pressures are required to return gas to the sand the gasoline content will be largely removed because of the necessity of

cooling the gas between stages of compression. The mechanical operation of the equipment will be better on dry gas.

When low pressures can be used it is recommended that the wet gas be returned to the sand. The gasoline present will dissolve readily in the oil, making it more fluid and at the same time increase both the gravity and volume of oil recovered. A large percentage of the oil remaining in the sand is in the form of a film adhering to the sand grains. Wet gas will wash or dissolve this film of oil in a more effective manner than dry gas. Under these conditions the film of oil will be accumulated as a liquid and forced on through the sands. In one instance called to the writer's attention, channeling or by-passing by the use of air or dry gas was eliminated by introducing wet gas. The gravity of the oil was also increased. A production engineer for a large oil company recently made the statement that wet gas for repressuring was worth 300 per cent. more for the oil recovered than for the gasoline royalty received by the producer.

Even with the use of wet gas considerable oil will be left in the sand, which cannot be recovered. It may be possible to make some profit from this oil because dry gas passed through the depleted oil sand will accumulate some gasoline.

A suggested procedure would be to repressure with wet gas until such time as the volume of oil recovered is no longer profitable, then extract the gasoline from the wet gas, returning the dry gas to the sands to become enriched by contact with oil remaining in the sand, and continue this process until no longer profitable, after which the gas remaining can be sold. It is practical to use the same machinery during the entire process.

Location of Pressure Wells

The character and size of the structure will govern to some extent the location of pressure wells. To be most effective the wells must be so located that practically all producing wells derive some benefit from the pressure. Where gas is found in the top of the structure and water under pressure surrounds the oil it is estimated that best results can be obtained by locating pressure wells down the structure and not far from the edge water line. Pressure thus applied will help to hold back the edge water and move the oil up structure. Other pressure wells located in the center of the oil zone will be necessary for proper distribution of pressure.

Some advantage might be gained by forcing gas into the gas zone on top of the structure. Gas is more compressible than oil and therefore much larger volumes could be forced into the gas-bearing part of the structure at the same pressures required to inject gas into the oil zone. Large volumes of gas could be stored in this manner and at the same time

force the oil away from the gas area to producing wells. Wells which will produce only gas or small volumes of oil with large volumes of gas should be shut in, otherwise the gas pressure will be reduced and the oil may migrate into the dry gas sand where a large portion of it will be unrecoverable.

In fields where strictly gas areas do not exist and oil is distributed more or less uniformly, the pressure wells should be located to give the best distribution of pressure to the entire area. If edge water is a hazard it should be taken into consideration when locating the pressure wells. Sometimes edge water does not have sufficient pressure to be a hazard, but simply acts as a dam about the field. This condition appears to hold for the second Wall Creek sand in the Salt Creek field where edge water advances very slowly even though the rock pressure has been greatly reduced by the removal of both oil and gas from the sand. The same condition, however, does not apply to the first Wall Creek sand, where edge water advances rapidly as the rock pressure decreases.

Ultimate Recovery

Estimates on ultimate recoveries that may be expected from early repressuring can hardly be more than guesses if based on the information at present available. Data that have been reviewed indicate increases from 30 to 60 per cent. over normal operations without an appreciable increase in the time element.

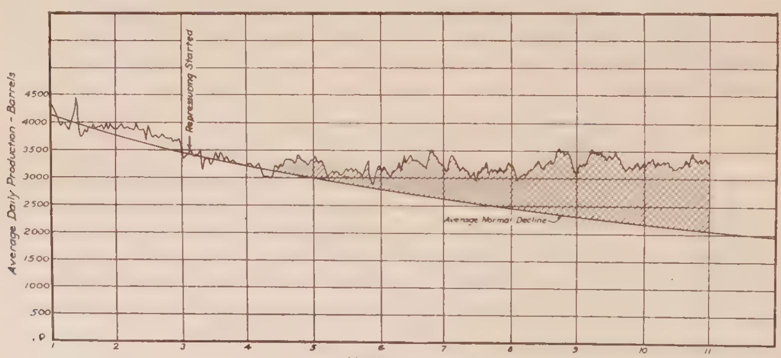

Fig. 1.—Lease decline curve showing results of early repressuring.

It is anticipated that a greater percentage of oil can be recovered from a single sand of comparatively uniform texture than from zones of producing sands which may be several hundred feet in thickness. This statement is based on the supposition that the thick zone will be made up of many sands varying in texture, saturation and porosity, and separated by beds of shale. Some of the sands will respond more readily to pressure and be depleted of oil before the pressure acts on the other

sands. The depleted sand will then act as a channel through which gas may pass. This condition is one of the hazards to be encountered and will be difficult to overcome, when applying pressure to producing zones of great thickness.

A few curves have been prepared for the purpose of illustrating some of the results being obtained by early repressuring. Fig. 1 shows a sustained production due to repressuring. For the period of 8 months following the date of applying pressure the actual production was 25 per cent. greater than the anticipated production as estimated from the decline curve. Fig. 2 shows another lease decline curve. The difference

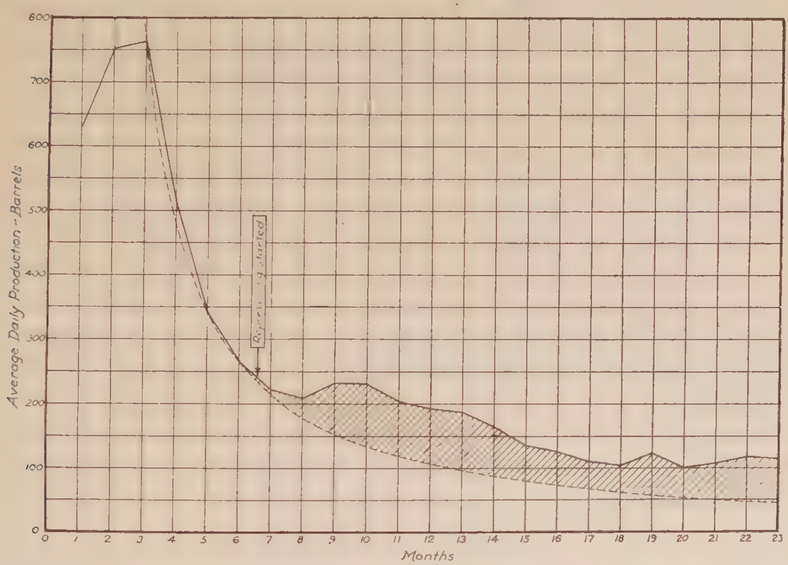

FIG. 2.—LEASE DECLINE CURVE SHOWING RESULTS OF EARLY REPRESSURING.

between the actual and estimated production as shown by the hatched area, represents an increase of 21.3 per cent. over the total actual production up to the time of applying pressure plus the estimated declined production from that date. It seems reasonable to assume that as a result of repressuring, the total oil recovered from this lease will be 30 to 40 per cent. greater than the normal decline would indicate.

COOPERATION ESSENTIAL

As pointed out by Henry L. Doherty, several years ago, increased efficiency in the recovery of oil can be attained only by some form of unit operation which will make possible the application of improved methods involving the maintenance of pressure.

It is clearly evident that neither back-pressure control nor repressuring can be successfully applied to a single lease of average size in any oil

field. Oil producers are beginning to realize this fact as evidenced by the growing tendency toward cooperative agreements, especially for repressuring operations.

As the advantage of cooperative or unit operation becomes more evident it will be only a matter of time until entire pools will be developed under conditions of pressure control. When this period is reached we can expect to see a marked increase in the efficiency of recovering oil, both as to volume of oil recovered and the cost per barrel.

Summary

1. With present production methods the amount of oil recovered depends on the efficiency with which the potential energy stored in the gas is used. For any given field this energy is limited.

2. Additional production can be expected by supplying more energy to the oil sand in the form of gas under pressure.

3. During the early stages of development gas is frequently wasted or inefficiently used. By returning this gas to the sand it will be conserved and also aid in recovering more oil.

4. When the rock pressure is high during the early stages of development the physical properties of the oil are such that it can be moved through the sand with less resistance. Therefore, more effective work should be obtained from the gas returned to the sand at this stage of development.

5. Repressuring started during the period of flush production should result in a greater ultimate recovery in a shorter period of time and at a more uniform rate.

6. High injection pressures are mechanically possible and should be practical.

7. Where pressure conditions will permit, wet gas returned to the sand will increase both the recovery and gravity of oil and decrease the hazard of the gas by-passing.

8. Gas returned to the sands under pressure will hold back the encroachment of edge water.

9. Fewer wells should be required to drain effectively a given area being repressured during the flush period of production.

10. Unit operation or cooperation in some form is essential for the successful application of improved methods for recovering oil.

Acknowledgment

The writer wishes to express his appreciation for the suggestions offered and data furnished by the following engineers: A. W. Ambrose, A. H. Bell, E. O. Bennett, E. V. Foran, T. F. Hudgins, A. C. Rubel, W. W. Scott, J. R. Suman, T. E. Swigart and M. R. Young.

DISCUSSION

J. F. Dodge,* San Francisco, Calif.—The only reason I am venturing to make any remarks is that for the past few months I have been familiar with the repressuring work in California carried on by the various oil companies through their reports to the Operators' Committee on Gas Conservation and so have a general picture of the situation there.

Mr. Beecher points out (page 139) the importance of repressuring early in the life of a field. From our California experience we can substantiate this to a great degree, particularly in the work done in the San Joaquin Valley. The Standard Oil Co. of California carried on some repressuring of the gas-drive type in this area and we found that even though repressuring operations are confined to sands 50 ft. thick or less, there has been apparently sufficient depletion of oil to cause serious by-passing. Gas put into one well might by-pass to wells several locations away. This is probably made possible by separation by gravity of the oil and gas in the producing sand, leaving the upper part of the sand drained of oil.

Later, Mr. Beecher mentions a point which I would like to stress: that is the fact that in producing sands varying in texture or porosity we find a great tendency for gas to by-pass through more porous sands where time has been given for these more porous sands to be depleted to a greater extent than the tighter sands.

Mr. Beecher mentions the fact that repressuring offers a means of conserving much of the gas which is wasted during the flush period of production. One of the outstanding projects in California is the proposed injection of gas in the Meyer zone, in Sante Fe Springs, where 40 operators will pool their interests and inject gas from the new deep zone with the idea of preventing wastage of gas at present and of conserving the gas for the future supply of the city of Los Angeles.

As to the rock pressures found—particularly in California—Mr. Beecher mentions the experimental work of the Marland Company at Seal Beach. This work has recently been discontinued.

In the Ventura field, the Shell Co. carried on experimental work, attempting to inject gas in the wells in that structure, but it has not been successful so far. It proposes further experimental work but there are other serious difficulties in that field which are diverting its attention for the present.

It is not believed that there are any insurmountable obstacles to the injection of gas at the high pressures necessary, but there is a scarcity of high-pressure equipment at present.

Mr. Beecher mentions the efficiency that can be obtained if you will so operate your property as to take gas into the compressors at high pressures. In connection with the Santa Fe Springs project, it is proposed to double-trap wells and obtain the gas at 150 lb. from the Buckbee Zone wells; to treat this gas in high-pressure absorption plants and deliver to the injection plants at that pressure. These are merely proposed plans, carefully worked out, which are to be presented to the operators assembled in Los Angeles.

In connection with the use of wet and dry gas for injection purposes, it might be of interest to know that the Standard Oil Co. of California is attempting in the Buena Vista Hills area to get away from some of the by-passing difficulties we had, by injecting gas containing about 85 per cent. propane, a very wet gas obtained from the top of the stabilizers of the casinghead gasoline plant. This gas is being injected into one well in order to determine whether the wet gas will cause less by-passing than dry gas.

The Union Oil Co. is injecting propane with dry gas in the Dominguez field. A week or so ago I was told that the Shell Co. had some similar project on foot, also in the Dominguez field.

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*Standard Oil Co. of California.

Mr. Beecher mentions the possibility of circulating dry gas through a depleted oil sand. The Honolulu Oil Co. has been doing this for some time in the Buena Vista Hills area of the Sunset-Midway field. Dry gas has been circulated through practically depleted oil sand and sufficient gasoline has been recovered from the sand to pay the cost of obtaining it and to give a profit.

As to the choice of location of pressure wells, we have found that the injection well should be chosen well down on the side of the structure. Last year the Standard began some gas-injection work in Los Angeles County and since gas storage rather than gas injection and its effect on production was then being emphasized, wells on top of structure were chosen. When the work was resumed this year we chose injection wells down the side of the structure and discontinued injection in the wells on the top of the structure. It is my understanding that in the Dominguez field they have not found that structural location had much to do with migration of gas. In that field this seems to be governed more by the location of the more depleted areas without regard to the structural location of producing wells. That field is much less depleted than the Murphy-Coyote field. The Murphy-Coyote field has been producing about 15 years, while the Dominguez field is a new one. Formation pressures are higher in the latter and the oil recovery from the sands has not reached the percentage attained in the older field.

As to the statement on page 144, regarding the water in Salt Creek, I am not informed, but from our experience we believe that it is not a question of water pressure but of mobility of the fluids concerned. The water is not as mobile a fluid as the gas drawn out and in following up the gas the time function enters. If the water were given time, even in the Wall Creek sand Mr. Beecher mentions, I believe it would probably follow up the gas and oil.

Fig. 1 is representative of the results obtained on the Union Oil Co. leases and on the Shell Co. properties in the Dominguez area.

There is one point on which I might take issue; that is, the necessity of cooperation. Cooperation in these injection projects is entirely and highly desirable, but we have been attempting to further injection projects in California in connection with the state wide gas conservation work and have been stressing the fact that it is not entirely necessary to have the cooperation of your neighbor; that you can do much good on even small pieces of property; that much less than a section lends itself to gas injection, if the amount of gas injected, injection pressures and the back-pressure control of the producing wells are carefully watched.

This somewhat Utopian scheme at Santa Fe Springs may fall through; I doubt very much whether the cooperation of all these men will be obtained, but there will be a considerable number of similar projects started, where the operation will be confined to a limited area by regulating the amount of injected gas and by the careful control of the producing wells.

C. E. Beecher.—I should like to ask Mr. Dodge if his company has made any effort to inject gas into the bottom portion of the oil zone in the San Joaquin Valley field as a means of eliminating by-passing and moving the oil in the lower part of the sand.

J. F. Dodge.—Very soon we shall begin a new injection project of the gas-drive type and will use wells on the edge of the structure—in fact, a brand new well, with the idea of trying to get the gas below the fluid, maintaining the fluid wall ahead of the migrating gas. Unfortunately, a very large part of the gas injection operations in California during the past year have been directed towards the storing of gas. We have a gas surplus of some 200,000,000 cu. ft. per day in Southern California and almost the entire attention has been directed toward storing rather than production assistance.

Just recently a change has come about, the domestic gas load increased enormously, and we have been able to change from gas storage to production aid.

The industrial and domestic gas load fluctuates widely; a short time ago we had a large surplus and at present we have no surplus of gas. Several days ago we discontinued storage on one project and may have to discontinue another.

This experimental work will be continued regardless of the gas consumption situation, as only small amounts of gas will be used.

C. E. BEECHER.—It is my impression that the upper part of the sand in the Buena Vista area has been drained of oil and is now occupied by gas under very low pressures. The sand, however, is still wet with a thin film of oil and therefore would not offer great resistance to the movement of oil which might be forced through it as a result of repressuring.

J. F. DODGE.—We hope to do that by using edge wells and new wells. The question is how far under those conditions the gas will actually travel. Under the present conditions, using the wells which are fairly depleted, there is a migration of gas.

A. B. MORRIS,* Tulsa, Okla.—What has been done in the direction of pumping gasoline into the pressure wells, that is, getting rid of the entire gasoline production by pumping it into the wells?

C. E. BEECHER.—There were a few projects operating under pressures of 30 to 60 lb. where the casinghead gas is returned to the sand without extracting the gasoline.

E. O. BENNETT,† Ponca City, Okla.—The work that has been done already indicates that it will probably be the economic thing to put all the gasoline back into the structure. On flush production, in the future, I think you will see no gasoline plants in operation. Possibly compressor plants will be put in, all the wet gas will be put back at the flush stage, until all production is out, then the dry gas will be pumped down and after the oil is taken up the gasoline will be available for a period of years and then vacuum pumps will be used. Thus there will be three outstanding cycles: (1) production with gas put back to maintain the pressure as long as possible; (2) recycling the gas, and (3) the third stage.

A. B. MORRIS.—If you do that it will stabilize the market. The gasoline market has been in bad shape for a long time. The exceptional production in the Seminole has broken the market for all the gasoline producers and it would be beneficial to use the gasoline for repressuring operations.

E. O. BENNETT.—On flush production there is a surplus of gas that should be used. If this gas were recycled to maintain pressure there would be less surplus at any time.

S. C. HEROLD,‡ Stanford University, Calif.—Repressuring, while appropriate in some fields, is entirely inappropriate in others. To make a determination of the case in any particular field we may prepare a well for pumping in a fair amount of gas, say 10,000,000 cu. ft. Presumably we know the closed-in pressure at this well before we begin pumping; after pumping we note the pressure. If there is no increase we should not repressure; if there is an increase, we should repressure.

The difference between the two types of reservoirs is a matter of the so-called "Jamin action." This phenomenon seems to be of the utmost importance in oil and

* Chestnut & Smith Corpn.

† Chief Engineer, Marland Companies.

‡ Petroleum Geologist.

gas production today. We cannot afford to ignore it. Where there is no increase in pressure, this action, due to alternating bubbles of gas and globules of oil, is subordinate, whereas an increase in pressure indicates the fact that it is predominant. In the latter case the act of repressuring cleans out an elliptical area between the input and output wells. The size of the ellipse is determinable; it is dependent on the intensity of the applied pressure, the porosity of the sands, and the surface tension of the oil. It becomes an easy task to figure out the percentage recovery from the field, for the ratio of recovery is the ratio between the areas of all ellipses and the area of the field at large.

I believe that we should allow our wells to produce as long as we can by natural flow, by air-lift or gas-lift, and by pump, before repressuring.

If we pump gas into reservoirs which are inappropriate for repressuring, we fill the top of the structure with a superabundance of gas; we "spread" the pool, and thereby push the oil down the dip to maintain edge wells in oil long after they would normally go completely to water. This does not happen in appropriately repressured reservoirs, since the edge water remains fixed in position throughout the history of production from the field. Wells within the pool never become edge wells by encroachment. The Coalinga field may be cited as one inappropriate for repressuring and the Cushing field as one appropriate for repressuring.

Where any reservoir is provided with input and output wells the injected gas should normally pick up the vapor from the oil with which it comes in contact, carry it to the output well, and thereby leave the by-passed oil of greater specific gravity and greater viscosity because of this loss of vapor. The injection of gas into oil will undoubtedly decrease the viscosity where the fluids are held in a closed container, or where there is but one orifice to the container. Obviously this should not be true where the container has two or more orifices. The dual situation is easily verified in the laboratory.

In fields appropriate for repressuring, there can be no increase of pressure within the reservoir where we relieve the pressure by taking away the oil at the output well as fast as we pump in gas at the input well. This process is permanent so long as any oil remains in the elliptical area between the input and output wells.

We should differentiate, I believe, between so-called "static effects" and "kinetic effects" of Jamin action. The former pertain to the fluids at rest within the reservoir, that is, with the well shut in at any time during its history as a producer, while the latter pertain to the fluids in motion with the well actually producing. As a matter of fact we are dependent on static effects for our ultimate production and on kinetic effects for our rate of production. Even where repressuring is inappropriate we benefit from kinetic effects in a greater rate of production at the time, while that which I have said before should indicate that we suffer from static effects in obtaining a much less ultimate production.

It seems to me that the effects of repressuring upon the ultimate production have been little considered. We appear to be interested largely, if not exclusively, in an increased rate of production, trusting to nature that this means increased ultimate production. This certainly does not follow.

There is a mathematical relation between rate of production and ultimate production worthy of being understood. Once we understand this mathematical relation the physical relation between them becomes clearer to us. The effects of our operations upon ultimate production can only be known by the study of theory, for in practice we will never have actual data pertaining to what might have been, had we done something other than that which we did. We need knowledge of mathematics and knowledge of physics. We may be assured that any question regarding production that is being put to us by the producer today can be competently answered by means of mathematics. It has served other industries in the past; it will serve ours in the near future.

Intermittent Injection of Gas in Gas-lift Installations*

By Morgan Walker,† Tulsa, Okla.

(Tulsa Meeting, October, 1928)

Intermittent injection of gas in gas-lift pumping is a variation of the common practice in that the gas is delivered to the well for a short period, called the "on time," followed by a period during which none is admitted, called the "off time," instead of being admitted continuously at a constant rate or by intermittent flowing in which it is occasionally delivered to the well in just sufficient quantity to flow off the accumulated head of fluid. The term "gas" is used throughout this discussion but it should be remembered that in so far as the operation is concerned either air or natural gas may be used.

The equipment at the well is the same as commonly used in gas-lift installations and gas may be admitted to either the tubing or the casing. It seldom occurs that all the wells on a lease can be pumped economically by intermittent injection from one header. Wells that have flow characteristics which permit their being handled together have their intake lines grouped at a central compressor station. Well groups may consist of two or more wells. The total volume of gas delivered by each group of compressors goes to one well at a time through a quick opening valve, each well connected to the header receiving its charge of gas in turn. Special cases may require a deviation from this arrangement. The distribution of the gas to the different wells is effected by an automatic timing device which operates quick-opening valves on the intake lines. The timing mechanism may be actuated by electricity, liquid or gas pressure. The essential factor in the operation of the timing mechanism is that as one intake valve is closed another must be opened.

Water-operated Timing Device

Timing devices operate the intake valves either directly, or indirectly by pilot valves. Of the former type one that is operated by water and has given satisfactory service is shown in Fig. 1 and can be made on the lease. The horizontal cylinder is a piece of 10-in. casing about 7 ft. long, closed at each end and free to oscillate about a fulcrum at the center.

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† Amerada Petroleum Corpn.

A partition in the center forms two compartments so that one may be filled while the other is being emptied. The drain pipe empties into a drain pond with the overflow from the supply tank and the water may be circulated. In order to give the cylinder a rapid starting movement the spring catches CC hold the cylinder until the filling compartment is heavy enough to overcome the tension on the spring. The weights are used to balance the cylinder for different time intervals. The valve levers move in the same direction but are fulcrumed on opposite sides with respect to the valve stem so that one valve is opened as the other is closed. Several designs of timing devices operating on this principal are in common use. This type can be used when the flow characteristics of the wells will permit only two wells to be pumped from the same header.

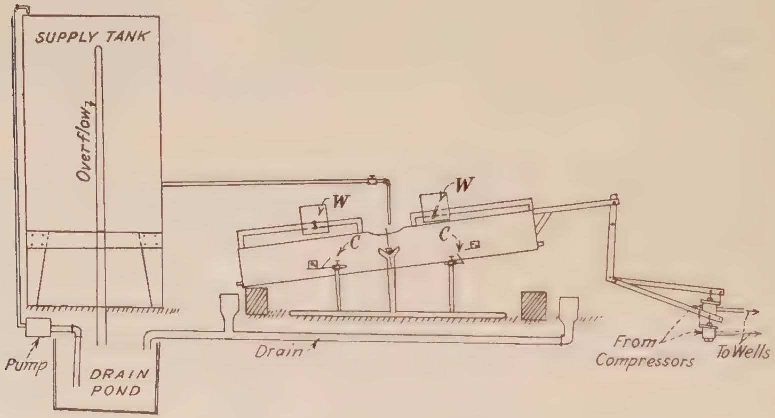

FIG. 1.—A FLUID-OPERATED TIMING DEVICE.

The indirect type consists of a timing device operating a pilot valve which in turn admits gas to a piston or diaphragm on the valve stem. These timers are actuated by a motor through a reduction gear. The electric type of timer is somewhat similar to the distributor on a multi-cylinder gas engine. The time is varied by changing the speed of the motor and the number of consecutive distributor segments connected to the solenoid which operates the pilot valve. The gas and liquid type of timer controls the pilot valve on the intake valve by suitable cams on a drum driven by the reduction gear. Variations of time are made by changing the speed of the motor and the length of the cams.

An additional relief valve is usually installed on the header and set to release at a safe operating pressure because there is a possibility that all intake valves on the header may, for some unanticipated reason, hold shut.

While the equipment necessary for intermittent injection of gas is being installed, gas may be delivered to the well continuously through a by-pass and the intake valve installed on the main line. After the

intermitter has been tested and the gas separated into the header the by-passes are closed and the gas is directed through the intermitter. If the wells are shut down for any length of time the breakout pressure may be excessive if gas is admitted to the wells intermittently due to the delivery of a large volume of gas and the high fluid level in the wells. Under these conditions the wells are usually started by continuous admission.

Determination of Time Interval

When the change from continuous to intermittent injection of gas is made it is necessary to determine the time interval that will give the most economical production. The procedure usually followed is to separate the gas required to flow two wells continuously into one header from which it is delivered to each well alternately and the volume and time interval changed until the best arrangement is found. If the wells will stand a longer off time than can be obtained with the two wells a third well is added and the best time interval and volume again found. This procedure is continued until all the wells that can be pumped from the header are added to the group. Although effective this procedure may require a great deal of time. In order to assist in obtaining the correct time interval as soon as possible resort was taken to the charts obtained from the orifice meters on the intake lines. The short-time interval and large fluctuations in volume made it difficult to analyze an ordinary 24-hr. chart as minutely as was desirable. The use of a clock movement that rotated the 24-hr. chart in 2 hr. enabled more accurate determination of the flow characteristics. A comparison of a 24-hr. chart and the same chart rotated in 2 hr. on the same meter under the same working conditions, is made in Figs. 2 and 3. Flow characteristics that cannot be analyzed on the 24-hr. chart are at once evident on the 2-hr. chart. These records are also valuable for future operation.

Waste in Pumping Energy

A well pumped by intermittent injection of gas to the tubing usually requires delivery of gas to the well after the breakout pressure is reached, because of the small volume of the line from the intake valve to the bottom of the tubing. Since more compressors deliver gas to the installation than would be necessary if the wells were pumped by continuous admission of gas, the compressors will deliver gas under a higher pressure than is necessary to bring the fluid to the surface. This wasted energy can be saved by determining the volume of gas required to flow each head and adding enough volume to the intake line so that the gas in the gas string under the breakout pressure is enough to bring the oil to the surface. On the other hand, if the volume of the gas string is too high, a

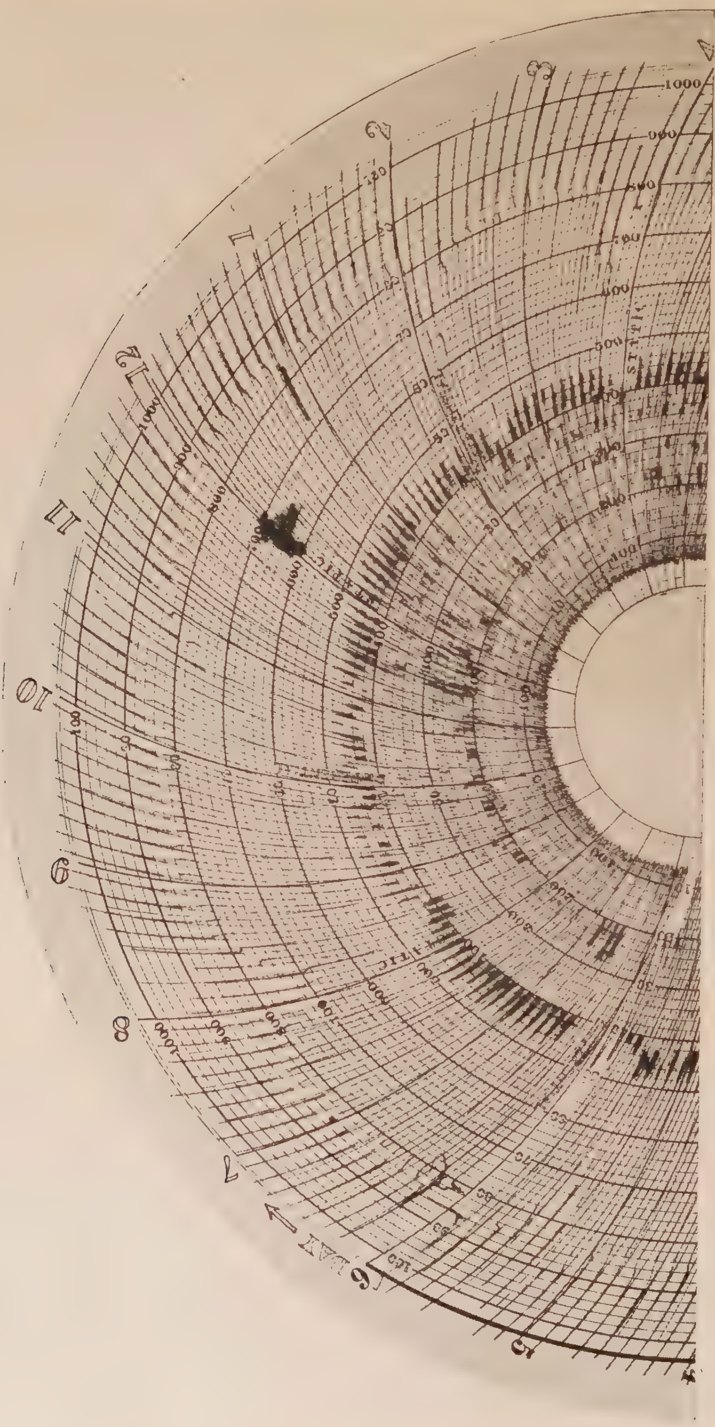

Fig. 2.—Twenty-four-hour orifice meter chart recording intermittent injection of gas.

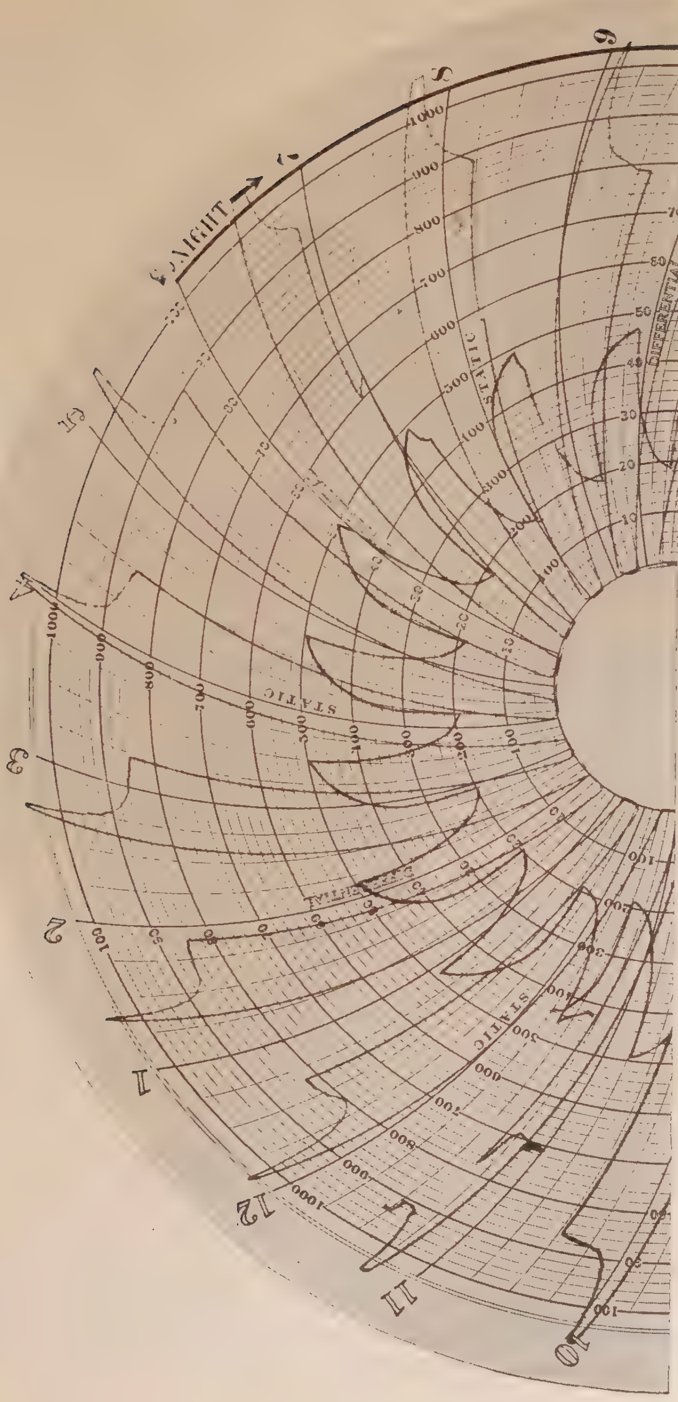

FIG. 3.—CHART TAKEN ON SAME METER UNDER SAME CONDITIONS AS IN FIG. 2, BUT ROTATED IN 2 HR.

waste of energy will result because the pressure must be raised enough to set the oil column in motion regardless of the volume of the gas string. This condition is more likely to exist when the oil is delivered through the tubing, especially if the intake line to the well is large. If the volume of the gas string is such that the volume of gas expanded from the line after breakout pressure is reached, is more than enough to bring the accumulated fluid to the surface, a waste of energy will result and the time required to drain the gas from the line will increase the average pressure on the sand, thereby decreasing the oil production.

Attempts have been made to reduce the maximum pressure required when flowing up the tubing by intermittent injection by the use of a small orifice in the tubing near the liquid level in the well. Some promising results have been obtained. One well making 30 bbl. oil per day was tubed to a depth of 4200 ft. with 2½-in. tubing. The lower 140 ft. was 3-in. tubing which formed a reservoir for the accumulated oil. A string of 1¼-in. tubing was run inside the 2½-in. and gas introduced between the 2½-in. and 1¼-in. Before the orifice was drilled in the 1¼-in. tubing a pressure of 660 lb. did not start the well flowing. After a ⅛-in. orifice was drilled in the 1¼-in. tubing 100 ft. above the oil level, the breakout pressure was 220 lb. and the volume of gas required to pump the oil was 55,000 cu. ft. per day. The time interval was such that sufficient time could be given for the gas admitted through the orifice to start the oil column in motion. If it is impossible to give the gas admitted through the orifice in the tubing time to set the oil column in motion the advantage is lost. The size of the orifice depends on the time interval as well as the pressure and volume of oil and water to be lifted. At present considerable experimenting is necessary to balance these factors properly.

Intermittent vs. Continuous Injection of Gas

Table 1 shows the effect on well conditions of intermittent and continuous injection of gas. The figures are for the period of continuous admission immediately preceding changing to intermittent injection, and for the period immediately following the change. The effect on production by continued use of intermittent injection is shown by Figs. 4, 5, 6 and 7, which are representative of average conditions and show that an increase in daily production accompanied by a decrease in inlet volume is obtained by intermittent injection. The variation in intake volume is due to admitting gas continuously for a time or to changing the intake volume to find the best flowing arrangement. Although the total fluid in some wells has increased there has not been a corresponding increase in the volume of intake gas which would probably have been necessary had continuous admission of gas been used. This is particularly noticeable

in Fig. 4. Also, in wells from which the daily oil production has decreased without appreciable increase in water the volume of intake gas has not been increased as much as it would were continuous admission of gas used. This is shown by Fig. 7.

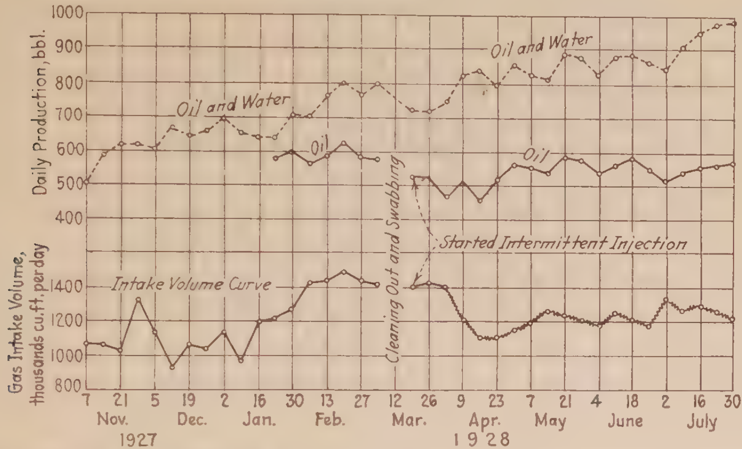

FIG. 4.—FIXICO WELL No. 4 PRODUCTION DECLINE CURVE SHOWING EFFECT OF INTERMITTENT INJECTION OF GAS.

The formational gas-oil ratio is usually increased by intermittent admission over that obtained by continuous admission of gas. This is shown in Table 1. The values of gas volumes given in this table have been calculated from planimeter readings of the differential and static

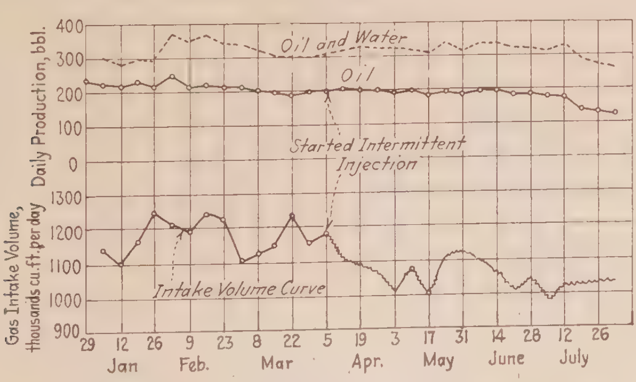

FIG. 5.—COWDEN WELL No. 1 PRODUCTION DECLINE CURVE SHOWING EFFECT OF INTERMITTENT INJECTION OF GAS.

curves taken on 2-hr. orifice meter charts so that accurate readings could be made of each pen movement. There is some doubt as to whether such violent heads of gas can be measured accurately even though extreme care is taken in reading the charts. Measurements of the gas taken at a

TABLE 1.—*Effect on Well Conditions of Intermittent and Continuous Injection*

Well	Water, Bbl. per 24 Hr.		Oil, Bbl. per 24 Hr.		Working Pressure, Lb.		Inlet Gas Volume, M. Cu. Ft. per 24 Hr.		Trap Gas Volume, M. Cu. Ft. per 24 Hr.		Formational Gas-oil Ratio, Cu. Ft. Gas per Bbl. Oil	
	Continuous	Intermittent	Continuous	Intermittent	Continuous	Intermittent	Continuous	Intermittent	Continuous	Intermittent	Continuous	Intermittent
Anderson No. 2	239	225	1077	1123	270	245	1516	906	1762	1775	228	773
Cowden No. 4	0	0	1087	1124	290	245	1525	1070	1750	1760	207	613
Nitey No. 3	0	0	986	1024	260	235	1301	897	1365	1135	65	232
Nitey No. 2	0	0	914	900	255	245	904	767	1171	1021	292	282
Nitey No. 4	0	0	873		200		1046		1281		269	
Fixico No. 3	96	116	400	475	286	288	1380	864	1410	1652	75	1660
Rentie No. 3	0	0	508	517	162	173	1014	937	1275	1322	514	745
Killingsworth No. 3	0	0	326	290	152	146	966	860	1082	1130	367	932
Cowden No. 3	0	0	279	285	185	180	1111	578	1220	1200	391	2180

gasoline plant meter which was far enough from the leases so that the heads were considerably damped out show that the results given in Table 1 are at least approximately correct. The increase in gas-oil ratio is

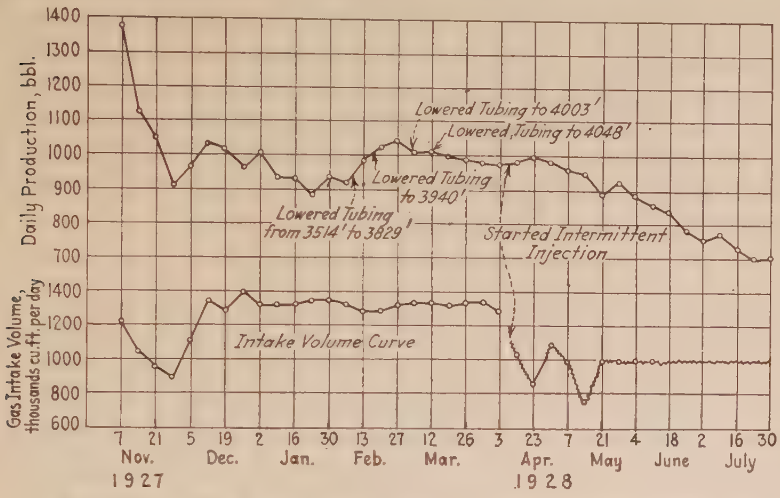

FIG. 6.—NITEY WELL NO. 3 PRODUCTION DECLINE CURVE SHOWING EFFECT OF INTERMITTENT INJECTION OF GAS.

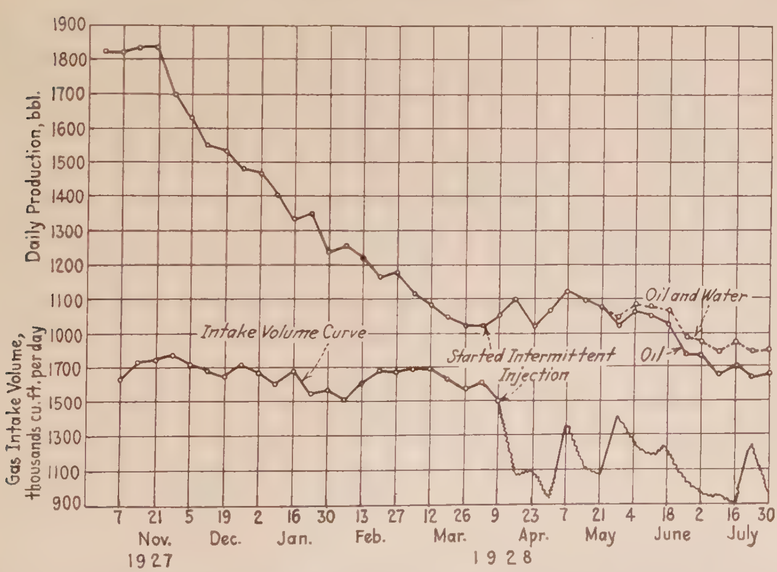

FIG. 7.—COWDEN WELL NO. 4 PRODUCTION DECLINE CURVE SHOWING EFFECT OF INTERMITTENT INJECTION OF GAS.

probably accounted for by the fact that the pressure at the bottom of the hole is lower during the off period than with continuous injection. When the rock pressure has fallen until the necessary working pressure decreases

the production, the pressure differential can be increased enough during the off period to obtain an increase in oil production with the accompanying increase in gas-oil ratio. Since the formational gas-oil ratio is increased there is a question as to whether it is economical to produce a well by intermittent injection of gas. It will be observed that the increase in rate of production is accompanied by an increase in formational gas-oil ratio which is at variance with the prevailing impression that an increase in gas-oil ratio will decrease the recovery. It is true that the data available are insufficient to warrant a definite conclusion but to date they indicate that the ultimate recovery is increased by the use of intermittent injection of gas even though the gas-oil ratio is increased.

Effect on Gravity

An increase in gravity of from 0.3° to 1° Bé. has been obtained by producing with intermittent injection over that obtained by continuous injection. This is probably due to a less intimate contact of the gas with the oil and therefore less distillation of the lighter constituents into the gas. The increase in formational gas-oil ratio, with less dry gas recycled may also have some effect on the gravity as well as account for the increases in the gasoline content of the gas.

Power Consumption

A comparison of the effect of continuous and intermittent injection of gas on power consumption is shown in Table 2. The data are from three leases on one of which there were four wells and on the other two three wells each. The values of power consumption given are averages for 10 days of continuous and the following seven days of intermittent injection of gas. The power requirement is less for intermittent injection but the pressures against which the compressors work are higher than for continuous injection. The pressure on a well may drop from 400 to 125 lb. during one time cycle but the discharge pressure from the compressors continues close to the maximum pressures of the wells as it

Table 2.—*Effect of Intermittent and Continuous Injection on Power Consumption*

	Continuous Injection	Intermittent Injection	Change Caused by Intermittent Injection
Production per day:			
Oil, bbl.	6,086	6,247	161 gain
Water, bbl.	426	530	104 gain
Power consumed, kw. per hr.	1,963	1,686	277 loss
Compressors used	22	18	4 loss
Inlet volume, M. cu. ft. per day	11,863	8,612	3,251 loss
Trap volume, M. cu. ft. per day	13,174	13,844	670 gain
Average operating pressure, lb.	229	224	5 loss

requires but a short time to build the pressure on a well above the operating pressure carried when it is pumped by continuous injection. For this reason compressors should be checked for maximum pressure operation before intermittent injection is begun.

Intermittent injection of gas to gas-lift installations affords a means of increasing production from wells on which the rock pressure has declined. There are not enough data available to determine the effect on wells in the early life but those taken indicate that less benefit is to be derived from intermittent injection in the early life of a well than in the later stages.

DISCUSSION

D. B. Dow,* Bartlesville, Okla.—The intermittent flowing method of producing wells on the lift in Seminole has become extensive within the past year, and from my observations, I would say that this method has proved satisfactory. With declining production, wells on the lift require more and more compressor capacity to obtain maximum production if the flow areas remain unchanged. As a consequence the producers in the Seminole field were forced to install more compressor capacity on a declining production or to increase the efficiency of the lift, if maximum production was to be maintained by the lift method.

My observations covering 67 wells that have been produced by the intermittent flowing method lead me to say that the alternative has been met and that the increased production efficiency of the intermittent method of flowing has offset the increased compressor capacity demanded by declining production. Of the 67 wells mentioned, 29 showed a substantial increase in production (averaging approximately 30 per cent.) when placed on intermittent flow. Possibly some of these wells would have produced as much on continuous flow if compressors had been available, but in a number of cases it was impossible to obtain this increase by continuous flow. Thirty-three wells showed no increase or decrease in production when placed on intermittent flow, and followed the same decline curve as shown on continuous flow. These wells were produced with approximately 25 per cent. less compressor capacity than required for continuous flowing. Two wells of the 67 dropped in production when placed on intermittent flow. Three wells were placed on intermittent flow immediately after completion or after drilling deeper, and no comparison can be made on them.

It has often been suggested that intermittent flow might increase production only temporarily, or that the ultimate production might even be lowered. I have no data indicating that this is the case but information on wells that have been on intermittent flow for 10 months shows the characteristic flattening in the decline curve corresponding to that shown on pumping wells in the same stage of production.

I agree with Mr. Walker that it is reasonable to expect an increase in the gas-oil ratio with reference to the gas removed from the sand, but my information indicates that this increase is much less than shown in Mr. Walker's paper.

Measurements of volumes into and out of a well are very difficult when there are such extreme conditions of flow and variations in the specific gravity of the gas as occur in intermittent flowing. In Seminole it is possible to obtain widely differing figures on gas-oil ratios from wells on continuous flow or on the pump, where gas measurements are much simpler, and in view of this, I hesitate to form any conclusions on gas-oil ratios where intermittent flow is involved.

Frequently wells making water cannot be produced satisfactorily on straight flow but will make their production when placed on intermittent flow.

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*Indian Territory Illuminating Oil Co.

Effect on Producing Wells of Shutting in the Offset Wells

By C. M. Nickerson,* Los Angeles, Calif.

(New York Meeting, February, 1929)

In times of overproduction such as the operators have been struggling against for the past several years it is the practice of the oil industry to shut in certain wells in order to reduce the flood of oil. The purpose of this paper is to present certain variations in production of oil wells when the offset wells are shut in. The scope of the study has been confined to California fields, and more especially to those of the San Joaquin Valley.

The accepted definition of a shut-in well is a well where production has been suspended by closing in the casinghead and tubing or by cessation of pumping. The immediate effect of such a procedure, of course, is to reduce the oil production from the lease, which is the result desired. However, it appears that certain types of wells vary widely in production of oil, gas and gasoline after adjacent wells have been shut in, which variation has a very material effect on the ultimate recovery of oil from the property. The increase or decrease in the oil production itself may not be of sufficient volume to occasion comment, but wide fluctuations in the gas and gasoline recovery under the changed conditions are of the utmost importance in the future recovery of oil.

The scope of this paper includes: (1) the effect on producing oil wells of shutting in offset wells, the wells being studied in three groups arranged according to their relative stages of depletion; (2) probable source of excess gas and the effect on the ultimate recovery of oil; (3) suggested procedure when wells are shut in; (4) methods that could be employed to prevent undue migration of gas from the shut-in area; and (5) the need for future studies of the situation.

Three Classes of Producing Oil Wells

For the purposes of this paper producing wells in California have been arranged in three groups according to the age of the well, or to the relative stage of depletion of the producing zones. The first group consists of those wells with a high fluid level, or in other words those wells whose fluid levels are a considerable distance above the top of the perforations. This type of well is in the flush period of its life and ordinarily produces

* Petroleum Engineer, U. S. Navy Department.

considerable volumes of wet gas, and is either flowing or has been placed on the beam a relatively short while. The second group consists of those wells with the fluid level just above, or even a short distance below, the top of the perforations. These wells have been producing for a considerable period, but still have substantial gas and gasoline production. In this group the gas is the major factor in forcing the oil to the well. In the third group have been placed those wells that are in the last period of commercial production. This type of well produces little if any gas; the production is necessarily very small; and the force of gravity and the driving effect of encroaching edge water are the main factors in oil recovery. Although this paper is mainly concerned with the second group, the effect of shutting in offset wells will be considered on each group in the order of the above classification.

Subsurface Conditions

In order to give a clear conception of the movements of oil through the producing zones of California oil fields the average subsurface conditions are mentioned briefly.

In most of the oil fields of California, oil is found in loose, unconsolidated sands and in sandy shales. The texture may vary from very fine sand to that which is fairly coarse. The thickness of the zone may vary from one to several hundred feet, the sand strata alternating with thin shale bodies. Unless intermediate edge water is encountered the entire thickness of the producing zone is open in the well through the perforated casing (Fig. 1). Each of the separate bodies of oil sand may have its own peculiar production characteristics, but ordinarily as much of the zone is open to production as is possible. Quite often in the early history of a field a well is placed on production from the upper portion of the zone, and later when production from that particular zone is partially depleted and when more accurate geological information has been compiled, it is deepened to lower productive strata in the same zone.

The wells studied in this paper are located in fields where the sands have considerable lateral extent, *i. e.*, migration of oil and gas from one location to another is the ordinary occurrence, and is not prevented by any lenticular character of the oil sands.

To sum up the above: the producing wells in a field where a shutting-in policy has been inaugurated have partially depleted the upper strata of the zone, because this portion has been on production for a longer period than the lower strata of the zone, which therefore remains more prolific. Due to large areal extent of the oil sands the shutting in of an offset well tends to increase the drainage area of the wells continued on production, while the drilling of the wells through the entire thickness of the producing horizon opens artificial channels between the several

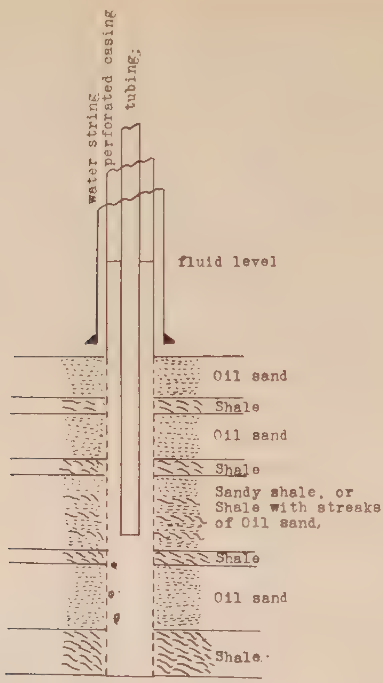

FIG. 1.—AVERAGE SUBSURFACE CONDITIONS IN CALIFORNIA OIL FIELDS.

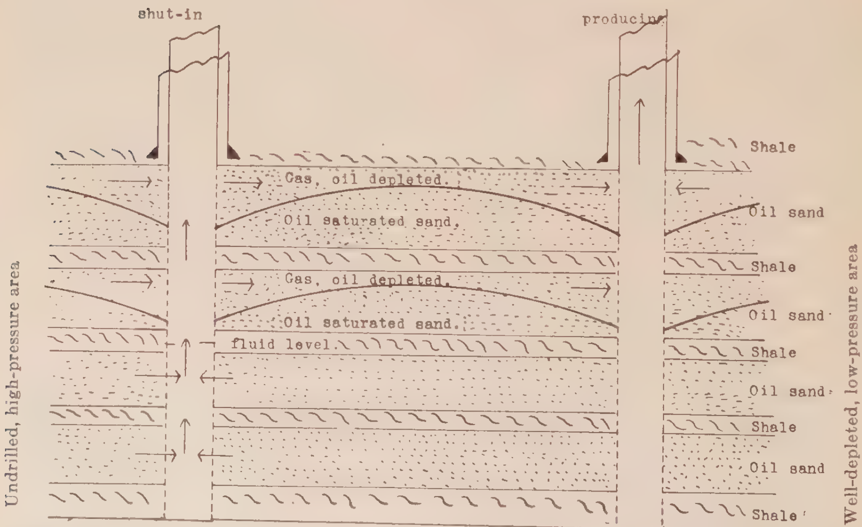

FIG. 2.—SUBSURFACE CONDITIONS WHERE WELLS HAVE BEEN PRODUCING FROM UPPER PORTION OF ZONE FOR A CONSIDERABLE PERIOD OF TIME, BEFORE BEING DEEPENED TO LOWER PORTION OF ZONE.

Arrows indicate possible course of gas from shut-in well to producing well.

individual strata, which may under certain conditions be the course of the migration of oil and gas from one portion of the zone to another and perhaps even from well to well.

Effect of Shutting in in Areas of High Fluid Levels—Group 1

During the flowing stage of flush production period in the life of the well the reservoir pressure is decreasing rapidly, especially in the area immediately surrounding the producing well. The fluid levels in such young wells are high, ranging from the surface to a considerable distance above the top of the perforations. Even after such wells have been placed on the pump, they are still ordinarily considered as in the flush state of production until the fluid levels have been materially reduced. This type of well has been placed in group 1 for purposes of comparison.

The subsurface conditions in such cases show the sands to be depleted only partially of the oil content. The face of the sand is still covered with oil, since the fluid level is well up in the casing, and the reservoir pressure is still rather high (Fig. 1). The production of oil is accompanied by considerable volume of wet gas with a good gasoline content.

When wells in this group are shut in, the offset wells continued on production have an increased drainage area, and ordinarily show an increase in oil production. The gas and gasoline production does not vary to any material extent, although the gas-oil ratio may be reduced somewhat. Under shut-in conditions for wells in this classification the production characteristics tend to approach those obtaining in the first few months of the life of the well, particularly in reference to gas production, its gasoline content, and the gas-oil ratio.

If wells in group 1, *i. e.*, in the flush stage of production, are shut in, there may be a marked decrease in oil recovery when they are again returned to production. However, this paper will not discuss the probability of changes in capacity of such shut-in wells, since it is concerned with the effect on the offsetting wells which are not shut in. In California it is the practice to shut in wells on fairly well depleted properties, and to continue producing those wells in other fields which are in the early stages of their flush period. Lease requirements and offsetting conditions are more apt to require continuing young wells on production than wells on those properties which have yielded a substantial portion of their oil content.

In conclusion, the effect on wells of group 1 which are not shut in include slightly increased oil recovery, corresponding increase in gross gas production, with slightly smaller gas-oil ratios, and in some cases an increase in the gasoline content of the wet gas. Due to the decrease in gas-oil ratios there appears to be an ultimate beneficial effect on the property as a whole, since the ultimate recovery of oil is increased.

Effect of Shutting in in Areas of Low Fluid Levels, with Substantial Gas Production—Group 2

Under the common drilling practice in California fields an oil property usually reaches its peak of flush production in the first year or two of its life, which indicates that the individual wells are also in the flush period of their life during the first two years. Following this period the wells decline rapidly, after which the decline curve flattens out accompanied by but a small decrease in oil recovery each month. There are still substantial volumes of wet gas obtained with the oil, but the property is considered as having passed its peak. This period covers roughly about 20 years, or until the lease is considered depleted of its oil and gas content. Wells which have passed their peak of flush production and are now undergoing a slow decline each month have been placed in group 2 for the purposes of discussion. Of course, there is a gradual change in production characteristics when a well passes from one classification to the other, a fact which must be borne in mind in considering the conclusions of this study.

In wells in group 2 the fluid level is commonly well below the top of the perforated casing or oil string, the production declines sightly but steadily each month, and the gas and gasoline recovery are of considerable volume. When wells that may be classified as group 2 are shut in, it has been found that the offset wells that are continued on production have important changes in volume of production, which unless clearly understood and properly controlled may adversely affect the ultimate recovery of petroleum from the lease.

In the Elk Hills oil field, California, a very extensive program of curtailing production has been in effect for about 18 months, about 50 per cent. of the producing wells having been shut in. An ideal situation for a study of this kind is obtained here with undrilled, proved areas offsetting the shut-in wells on one side and producing wells offsetting them on the other. The effect of the undrilled, proved areas on the producing wells serve merely to magnify the changes in production characteristics, which would occur in any other area classified under group 2.

The general subsurface conditions have been illustrated in Fig. 2, which shows the writer's conception of the partly drained oil sands in the upper portion of the hole and the well-saturated oil sands in the lower portion. The face of these lower sands is covered, since the fluid level is below the top of the perforations, while the face of the sands first encountered in drilling is uncovered due to the low fluid level, and undoubtedly have little oil in the upper portion of their individual strata. The voids formerly filled with oil are now filled with wet gas that has escaped from the sands adjacent to the well. If the sands have con-

siderable areal extent, it is very easy to conceive of a channel from well to well at the upper portion of the zone, which is depleted of oil and is filled with wet gas. It is this channel that apparently accounts for the remarkable increases in gas and gasoline recovery by the wells which offset those shut in. In fields where the producing zone is lenticular in character such a channel could not exist except in a limited area between a very few wells. However, these conditions obtain in but few California fields. In Fig. 2 the undrilled, proved area is indicated to the left, with the entirely

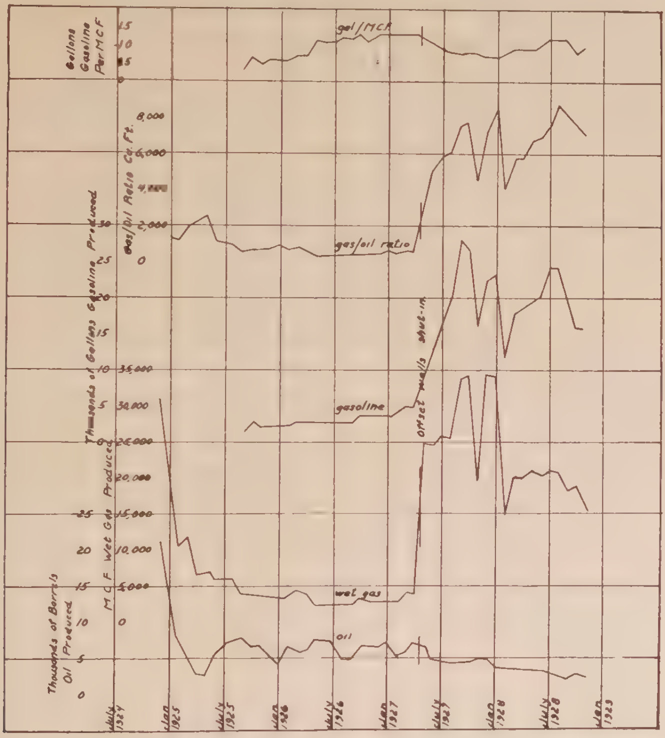

FIG. 3.—TOTAL MONTHLY PRODUCTION CURVES, INDIVIDUAL WELL.

drilled, well-depleted area to the right. The rows of shut-in wells are not indicated by other than the one well log, with the wells on production shown by the theoretical log on the right. If one line of wells or several lines were shut in, the effect would be the same on the offsetting lines wells or in decreasing amounts on several adjacent offsetting lines of wells.

For the ideal situation in the Elk Hills oil field, production curves have been prepared for the total production from two lines of producing wells that offset two lines of wells that were shut in. Individual well curves for certain of these producing wells have been prepared, which

serve to illustrate better the effects noted. These are discussed in detail in the following paragraphs.

The monthly production data for an individual well in this field which offsets a group of shut-in wells are given in Fig. 3. When certain wells were shut in on April 15, 1927, the offsetting producing wells showed an immediate increase in the volume of gas produced, a decrease in the oil production, and also a remarkable increase in gallons of natural-gas gasoline recovered from the wet gas. With these three values as a basis

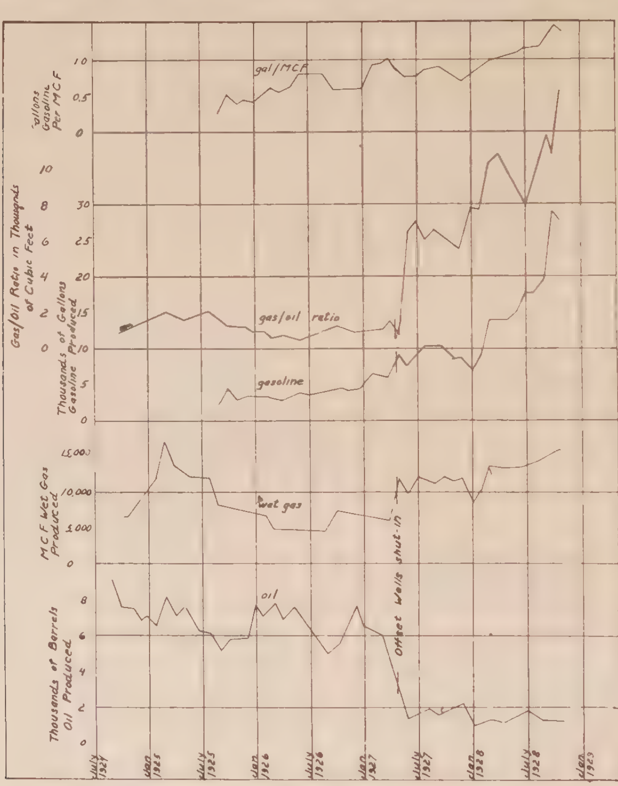

FIG. 4.—TOTAL MONTHLY PRODUCTION CURVES, INDIVIDUAL WELL.

several ratios were computed and plotted as given in Fig. 3. An analysis of these shows that the gas-oil ratio increased to more than nine times the former average value prior to the shutdown, while the gallons of gasoline per M. cu. ft. decreased to approximately two-thirds of its former value, although the gross gallons of gasoline obtained from this well increased about sixfold. Operating conditions remained the same from about Jan. 1, 1926, the well having been placed on the pump at this time.

A study of Fig. 3 shows that a considerable volume of gas came into the hole immediately following the shutting-in of the offsetting wells,

that this gas had a lower gasoline content than that obtaining prior to April 15, 1927, and that this excess volume of gas was by-passing the oil in the productive zone, since the barrels of oil did not increase. The slight decrease in oil production may have been due to the excess gas coming into the hole at its upper levels under a sufficiently greater pressure than that in the lower portions of the well, where the greater portion of the oil is obtained, to exert a back-pressure on these lower sands. The same decrease in oil production could have been obtained in

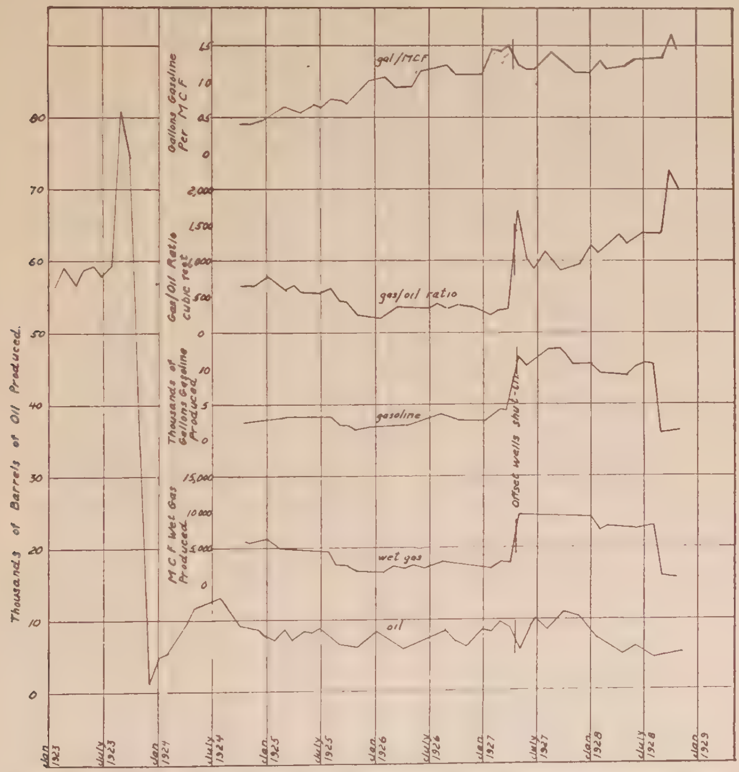

FIG. 5.—TOTAL MONTHLY PRODUCTION CURVES, INDIVIDUAL WELL.

this well by increasing the back-pressure, although it is rather doubtful if the volume of excess gas could have been decreased to any material extent.

Similar production curves for a well in this group and in the same field are given in Fig. 4. Certain of the effects mentioned above are emphasized in the case of this individual well. The oil production decreased to a very considerable extent; the gas production increased to about twice its former value; the gallons of gasoline recovered increased about 50 per cent.; the gas-oil ratio increased to about seven times its former average value, while the gallons of gasoline per M. cu. ft. of wet

gas decreased somewhat, but would average about the same as before over a period of a year. Again a study of this individual well shows that large quantities of wet gas had access to the hole and that the oil production was decreased, probably due to the pressure against the producing oil sands of the incoming gas. The excess volume of wet gas certainly did no work in bringing additional oil into the hole, and may be held to have by-passed the oil back in the sands, due to the subsurface conditions illustrated in Fig. 2.

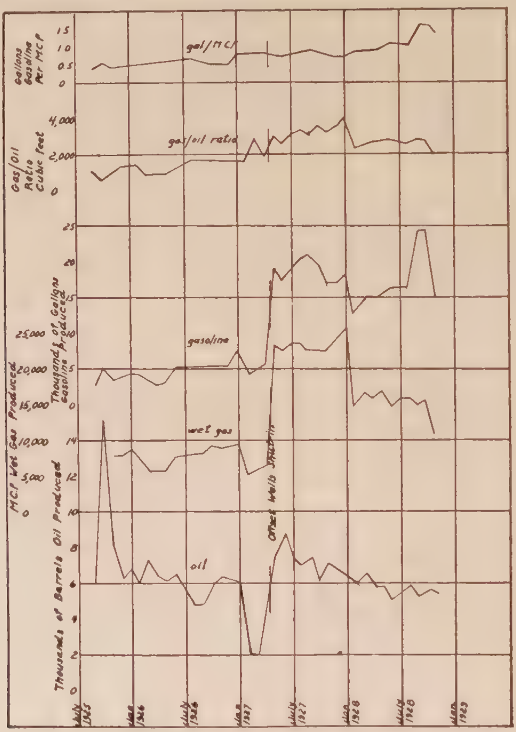

FIG. 6.—TOTAL MONTHLY PRODUCTION CURVES, INDIVIDUAL WELL.

Production curves for a well on the same property operating under the same conditions are given in Fig. 5, which show a slightly different effect from shutting in the offset wells than has previously been noted. In this case the oil production for each month increased somewhat and remained above the projected decline curve for about a year following the shutdown; the gas production increased about three times its former value; the gallons of gasoline accompanying the wet gas increased about three times. The gas-oil ratio immediately reached a peak, and the second month following the shutdown settled down to about three times the normal value, while the gallons of gasoline per M. cu. ft. of wet gas did not show any undue variation over the year's period.

In the case of this well the excess volume of gas obtained following the shutting-in program probably brought a considerable volume of oil into the hole, although the efficiency of the well was far below its former value due to the increase of the gas-oil ratio. The great increase in the gallons of gasoline recovered showed that the gas was picking up light fractions of the oil through which it passed in about the same ratio as before the shutdown, as brought out by the gallons per M. cu. ft. curve.

Curves for another well in this group with very similar production characteristics are given in Fig. 6. In this case the oil production was

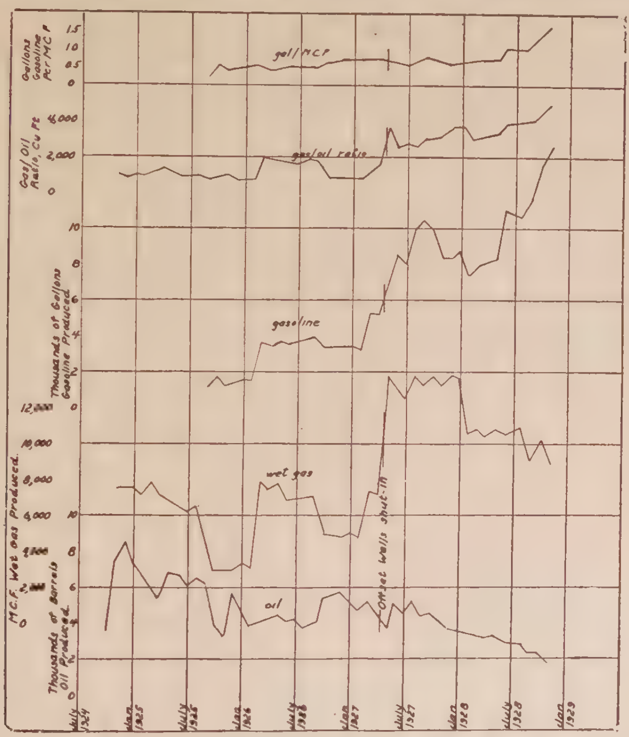

FIG. 7.—TOTAL MONTHLY PRODUCTION CURVES, INDIVIDUAL WELL.

increased by a very appreciable amount and the gas and gasoline production was about quadrupled. The gas-oil ratio increased about one-half, while the gallons per M. cu. ft. remained about the same. It is noteworthy that in the months following the shutdown the gas-oil ratio was steadily increasing, while the oil production was just as steadily falling off. The larger volume of gas obtained from this well apparently increased the oil production, but at the expense of efficiency, which became less each month as the volume of gas increased.

Fig. 7 illustrates production curves of an individual well in this same group located on the same property as the wells previously discussed.

The effect in this instance was slightly different from those previously discussed. The oil production followed the normal decline curve with but little variation; the gas production increased, as might be expected, to about twice its former volume; the gallons of gasoline recovered increased to about twice the former amount. The gas-oil ratio increased

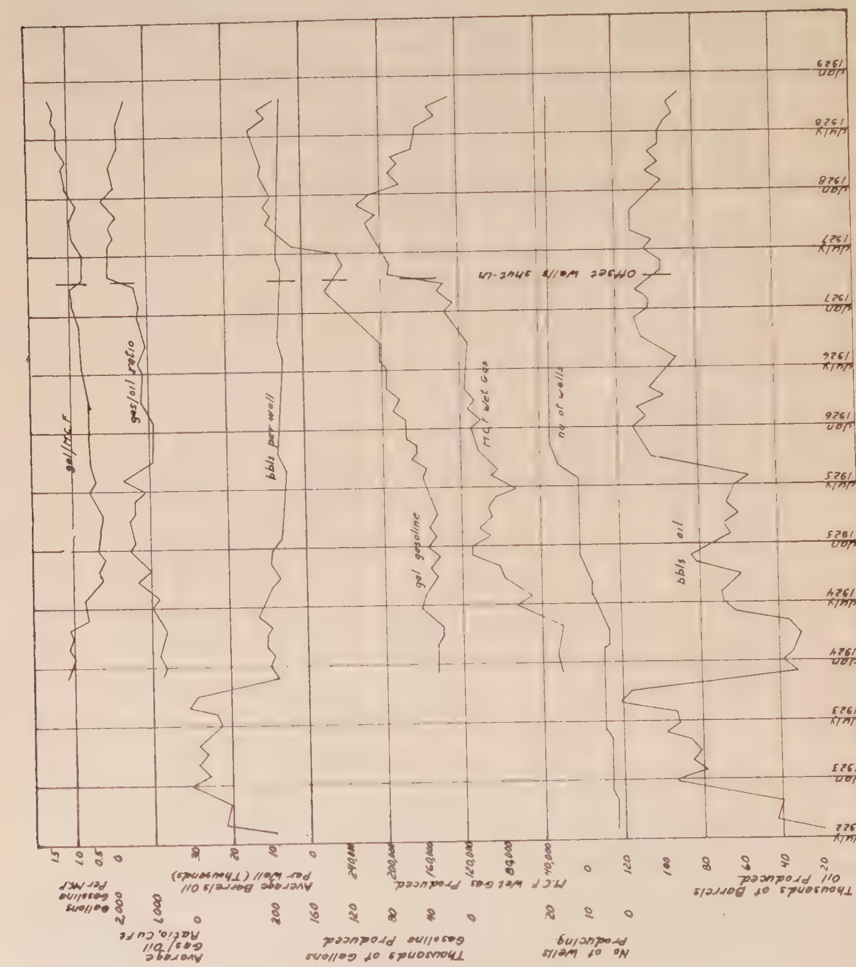

FIG. 8.—TOTAL MONTHLY PRODUCTION CURVES FOR LEASE, 17 WELLS.

from 1500 cu. ft. per bbl. of oil to an average of about 3400 cu. ft. The gallons of gasoline per M. cu. ft. of wet gas remained about the same. As before, a large volume of gas had access to the well, but it did not bring any oil with it, probably by-passing the oil in the sands some distance from this location.

In order to show the effect on a group of producing wells that are offset by an equal number of shut-in wells, curves have been prepared for the

several factors which are given in Fig. 8. These curves are based on the total monthly production from 17 wells located on a small lease in the Elk Hills oil field. The several individual wells previously discussed are located on this lease. The property had passed its flush stage of production and is now in the period of slow decline.

Fig. 8 shows that when the offsetting wells were shut in on April 15, 1927, the monthly oil production steadily increased for several months and then resumed the normal decline. The gas production from the lease about doubled in a very few months, and after the period of a year was still abnormally high. The gasoline production dropped off for about three months following the shut-in and then increased 50 per cent. over the expected volume. The gas-oil ratio shows that prior to the shutting in of the offset wells 1300 cu. ft. of gas were produced with each barrel of oil, while immediately following the date of shut-in 2000 cu. ft. of gas accompanied each barrel of oil. It is well to bear in mind in considering Fig. 8 that these curves show the average effect on the 17 wells on this property, and the individual wells previously discussed may vary from the trend of the graphs for the entire property.

In summation, the effect on producing wells of shutting in offsets in areas where the flush period of production is past includes a slight increase in oil production, a very substantial increase in gas and gasoline production, and a large increase in the gas-oil ratio. Although there is an increase in oil produced for a few months, the great increase in the gas-oil ratio shows that this excess oil is obtained at the cost of efficient production.

Effect of Shutting in in Areas of Low Fluid Levels and Depleted Gas—Group 3

When wells have about reached the limit of commercial production, the force of gravity is the prime mover in bringing the oil into the hole. Such wells produce little if any gas. If wells are shut in on a property placed in this classification, about the only effect resulting is the increase of the drainage area of each well continued on production. There may be a small increase in oil production, but ordinarily there will be no change. In California this type of property in many instances is shut in for as long as several years, to await an increase in the price of oil that will justify continued operation of the lease. For wells in this group it will be sufficient to conclude that little change may be expected in volume of production from individual wells when the offset wells are shut in.

Probable Source of Excess Gas and Effect on Ultimate Recovery of Oil

Since the ultimate recovery of oil depends to a very material extent on the volume of gas accompanying it, it is of the utmost importance that gas-

oil ratios be maintained as low as possible, especially on leases where shut-in wells may be offsetting wells that are continued on production. The changes in production characteristics that may accompany a shutting-in program on leases partially depleted of their oil content have been mentioned in the previous part of this paper. The source of the excess gas, and the channel by which it reaches the producing well, must be considered before any remedial measures may be taken to maintain efficient recovery of oil.

As mentioned under "subsurface conditions" the upper portion of the oil zone is quite often partially depleted of its oil content, the voids in the oil sands now being filled with wet gas. These conditions are illustrated in Fig. 2, which shows the upper portion of the individual strata of oil sand filled with oil and gas that have separated into two zones due to the forces of gravity and capillary attraction. The arrows indicate the possible channels by which the wet gas may migrate from one well that is shut in to an adjoining well that is continued on production.

From a consideration of the actual monthly production graphs previously discussed the conclusion is inevitable that a large volume of gas had access to the producing well and that this excess gas did not bring any extra volumes of oil with it, indicating by-passing of the gas. In order for the gas to by-pass there must have been a channel which contained little oil through which the gas could reach the producing well without doing any useful work. While by-passing the oil in the sands the gas picked up the lighter fractions resulting in an increase in the volume of natural-gas gasoline produced by the well. It is not necessary to conclude that the excess gas by-passed the oil in the upper portion of the zone only, for it may also have by-passed it in the lower portions of the zone, reached the shut-in well, migrated vertically to the upper portion of the zone, and then traveled horizontally to the nearby producing well. If the gas had traveled horizontally in the lower portion of the oil zone, it would have forced a certain volume of oil to the producing well, thus increasing the volume of oil production. In cases where this apparently has occurred the shutting in of a well has increased the drainage area of the offset producing well. However, the very substantial increase in gas production with increases in the gas-oil ratio leads to the conclusion that the gas was by-passing the oil surrounding the shut-in well, and reaching the producing well without doing any appreciable useful work. The low fluid levels, *i. e.*, below the top of the perforations, in the shut-in wells facilitated the migration of the gas from the lower portions of the zone to the upper portion where it traveled horizontally to the offset well.

To recapitulate, the source of the excess gas was from the zone surrounding the shut-in well, and the channels by which the excess gas traveled to the producing well are indicated by arrows in Fig. 2, which

shows the upper portion of the zone partially depleted of its oil content and now filled with wet gas. Although some of the excess gas may have traveled horizontally through the lower portions of the zone, as shown by the increase in oil production from certain of the wells herein considered, the major portion of the gas performed no useful work in bringing oil to the hole, due to by-passing the oil back in the sands surrounding the shut-in wells. The production of such excess quantities of gas without a corresponding increase in oil recovery indicates that the ultimate recovery of oil from this property has been considerably decreased.

Suggested Procedure in Shut-in Areas

When wells are shut in, the usual method in recording production data from the offsetting producing wells should be carefully studied in order to guarantee accurate daily data on the production of oil, of wet gas, and of the gasoline content of the wet gas. The average operator pays insufficient attention to these details of production engineering at the present time.

In areas having a large number of shut-in wells, the daily oil production should be gaged for the individual wells. A 24-hr. gas-production test should be obtained for each well, with frequent determinations of the gasoline content of the wet gas. The common practice of taking a test of the gas production once a month, or even at intervals of several months, leads to inaccurate proration of the total gas production from the lease, which in turn greatly handicaps the petroleum engineer in his efforts to obtain the largest possible ultimate recovery of oil. The casinghead pressure on the shut-in wells should be noted frequently, and if practical the changes in fluid level should be recorded. In this manner the true reservoir pressure can be obtained, since the fluid head of the oil in the well plus the casinghead pressure gives the pressure at the bottom of the hole.

On those wells from which a large increase in gas production is noted, the fluid content of the several members of the producing zone could be better determined by running a packer on tubing and setting the packer in successive steps below the top of the perforations. This will be successful in those fields where the plastic character of the shale has resulted in the shale closing in against the perforated casing, thus preventing vertical movements of the oil outside of the casing. From what little data are available at the present time, it is anticipated that the larger portion of the gas, with small volumes of oil, will be found to be coming from the upper portion of the zone, while the lower portion of the hole will be yielding the greater volume of oil, with its own gas-oil ratio.

Remedies to Prevent Undue Migration of Gas

Due to the partially depleted oil sands and their considerable lateral extent in the average California field, it appears that gas is very liable to

migrate from a shut-in area to wells nearby that are continued on production, as shown in certain instances by the several curves herein discussed. Any remedial work undertaken should be planned to prevent the migration of the gas from one zone to another, and also to prevent the gas by-passing the oil.

By producing a well through tubing with a packer set below the top of the perforations the fluid coming into the hole could be limited to that in the lower portion of the hole. In order to determine the proper place to set the packer, careful oil, gas and gasoline data should be available for the individual well. Lowering the packer a short distance at a time below the top of the perforations and noting the casinghead pressure and the daily production volumes of oil, gas and gasoline would very quickly indicate that the portion of the oil zone containing a large amount of gas and little oil is at the upper portion of the perforations, where it may be closed off behind the packer, or better, above the packer. In this way the pressure of the excess gas in the upper portions of the zone, under shut-in conditions, would be kept off the oil sands, and would not prevent the oil from coming into the hole. Also, the oil produced would have its own gas-oil ratio and could be produced much more efficiently. The writer fully realizes the dangers of setting a packer below the top of the perforations in certain California fields, where dangers of sanding-up are considerable. The use of a packer as just described would depend upon individual conditions.

Another method of preventing undue migration of gas would be to fill the shut-in well with mud fluid to a sufficient height to offset the normal reservoir pressure, thus preventing vertical migration of the gas from one stratum to another through the well. Of course, if the sands are so depleted that the use of mud fluid would permanently kill the well, this method could not be used, but if the reservoir pressure is at all substantial, it is anticipated that the well could be cleaned out and returned to production without any deleterious effects due to use of mud. Whereas this method would prevent vertical migration through the well itself, it would not prevent horizontal migrations of excess gas in the upper portions of the zone.

A third method that perhaps would prove feasible would be to produce the well through tubing with packer set below the zone of large gas production, and to close in the casinghead. By noting the building up of the casinghead pressure a reliable estimate might be made of the normal reservoir pressure, considering, of course, that any rise in fluid level above the packer in the annular space between tubing and casing would affect the determination of the true reservoir pressure. Then by injecting relatively small quantities of gas into the casinghead the normal reservoir pressure could be maintained and the gas held in solution in the oil in the upper portion of the zone. The amount so injected would be sufficient to

offset the normal reservoir pressure, and would tend to prevent the by-passing of the gas that ordinarily would reach the producing well and be classed as excess gas.

The use of back-pressures to decrease the gas production and also to maintain an efficient gas-oil ratio is very well understood and need not be discussed here. Under the conditions obtaining in the wells previously discussed the increasing of the back-pressure would serve to decrease the volume of excess gas coming into the hole, but it would also place an abnormal back-pressure on the zone which yields the major portion of the oil, probably resulting in a great decrease in oil production, but with little increase in the efficiency of the gas produced.

Necessity for Future Study

While it is a relatively simple matter to curtail overproduction of oil in fields in their flush period by merely holding high back-pressures, etc., it is quite another matter in fields past the flush stage to shut in producing wells and continue offset wells on production, due mainly to the difficulty in preventing migration of gas from one stratum to another and from one well to another. The great decrease in production when shut-in wells are opened up, in some cases considerably below the normal expected decline, may be traced directly to the production of excess gas from adjoining wells and leases during the period of shutdown.

There is a very vital need for more accurate data for the individual wells on the production of oil, gas and gasoline, and also of the casinghead and tubing pressures. The subsurface conditions in the average field may be very well understood from a general viewpoint, but since each well is an individual problem, more accurate data are needed on the character of the formations passed through, especially in the oil zone itself. The use of the core barrel for every foot of the distance drilled through the producing horizon would lead to accurate correlations between wells, and perhaps would indicate the course taken by the oil and gas in their movements between the wells. The careful testing of the fluid content of portions of the oil zone should lead to a better understanding of the production characteristics of each individual stratum penetrated by the well.

While the writer has suggested several methods to prevent undue migration of gas, these methods have not been tested sufficiently to guarantee results. The development or invention of a packer that could be set below the top of the perforations without sticking the packer or ruining the hole would be of great benefit to the industry.

In the event of curtailment of production in partly depleted areas, and in view of what has occurred on certain leases offset by shut-in wells, it would be well to consider a repressuring program by use of certain of the shut-in wells, which perhaps could lead to a smaller number of wells being

continued on production. In this way the ultimate recovery of oil from a field should not be endangered by the production of excess gas from producing wells offset by shut-in wells. The increased production obtained by repressuring could be obtained from fewer wells, although the total monthly production of oil from the field or lease as a whole would be materially decreased. It appears from studies at the present time that the damage to the producing measures is caused by the wells that are continued on production; hence any method that yields the desired volume of oil each day, but results in a smaller number of wells being on production, should minimize the damage to ultimate recovery of oil due to the migration of gas through the partly drained oil measures.

Conclusions

1. Subsurface conditions in the average California oil field that is partly depleted of its oil and gas content, *i. e.*, past the flush stage of production, show that the upper portion of the zone contains mainly wet gas, while the oil is found in the lower portions of the measures.

2. If wells in the flush stage of production are shut in, the offsetting producing wells will have a larger drainage area. The production will vary according to size of this area, the volume increasing somewhat, the gas-oil ratios remaining the same or even decreasing.

3. In areas where the wells are in the pumping stage and where the fluid level is low, *i. e.*, below the top of the perforations, the gas production still being of considerable amount, shutting in of wells results for the adjoining wells in an increase in oil production, a great increase in gas and gasoline production, and the increase in gas-oil ratios to the maximum of inefficiency.

4. In areas where gravity is the principal force in bringing oil to the well little change is noted by shutting in wells.

5. The great increase in gas production in areas discussed under group 2 is due to the gas migrating from strata surrounding the shut-in well and traveling to the producing well, by-passing the oil on the way, and bringing little additional oil to the hole.

6. The net result of producing excess quantities of gas under these conditions is to curtail seriously the ultimate recovery of oil from the shut-in wells, and also from the field.

7. Accurate daily determinations of oil, gas and gasoline production from individual wells will very quickly show any sudden increase in gas production, under these conditions, indicating the necessity for immediate remedial action.

8. The use of mud fluid in the shut-in well would tend to prevent vertical migration of the gas from one stratum to another through the medium of the connecting passage established by a well. Producing a well through tubing with packer set below the top of the perforations

would tend to prevent horizontal migration of the oil, since the pressure could be maintained on the upper portion of the zone.

9. In some cases the maintenance of sufficient back-pressure on the producing well would tend to prevent the production of excess quantities of gas, although it would probably put an abnormal back-pressure on the oil sands in the lower portion of the hole.

10. When it is necessary to curtail production by shutting in wells, a repressuring program should be considered, planned to prevent undue migration of the gas and to increase the future recovery of oil from the shut-in wells when they are again put on production.

DISCUSSION

J. B. Umpleby,* Oklahoma City, Okla.—The conclusions seem to follow logically from the facts available, but they necessitate vertical uniformity in the sand body, which I believe to be rare. Difference in the porosity of successive rock layers exist which cannot even be detected with the microscope, as is well known to students of contact metamorphic replacement phenomena. Similar differences are common in successive layers of an oil sand. I watched in detail a great number of water-flood wells in Bradford field, where the sand, until recent detailed studies, was considered remarkably uniform. In observing flood wells we plotted curves showing the amount of water and amount of oil based on daily gages. It came out most strikingly that when oil decreased water increased practically barrel for barrel. We interpreted the successive steps in the curve as representing the successive flooding out of different layers in the sand. In one group of 40 wells there were 26 distinct steps in the curve during the time when the wells were coming to make more water than oil.

Many other specific cases might be cited showing that absence of horizontal stratification or bedding planes in a sand body is exceptional. What would normally happen, I believe, would be that the production of the wells produced would increase and the total gas-oil ratio, if it changed, would decrease.

L. C. Uren,† Berkeley, Calif.—I wonder whether, in that left hand well (Fig. 2) that is shut in, the fluid level would not rise in the lower sands and shut off the upper sands. It seems to me to preclude any possibility of gas rising through the wells in the manner suggested. I believe we can explain the additional quantity of gas entering the right-hand series of wells on quite another basis than by escape through the overlying beds.

When the additional quantity of gas in the sand to the left in the sketch was made available to the right-hand wells, that greater volume, under high pressure perhaps, possibly takes possession of the drainage channels toward the right-hand wells, so that a larger percentage of gas is moving in the fluid toward the right-hand wells than formerly. I have noted that action many times in experimental work where gas might short-circuit through a sand and take complete possession of an outlet and yet the sands about the well might be nearly saturated with oil. Personally I should be inclined to put that interpretation on this particular case.

It is of considerable importance to reach a decision on this point, inasmuch as the wells shut in on the left are protecting Naval Reserve oil in the Elk Hills and obviously the Reserve is being drained of gas by the wells still in operation.

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* President, Goldelline Oil Corpn.

† Professor of Petroleum Engineering, University of California.

We might also question whether or not the increase in gas-oil ratio in the right-hand wells, which followed the shutting in of the left-hand wells, really means lower ultimate recovery. I should particularly like to know what the gas-oil ratio of the left-hand series of wells was before they were shut in. I would guess they had gas-oil ratios materially higher than those on the right, for the reason that they are merely offsets in closing a large undrained tract of land on the left of the sketch and we might perhaps find, if we had those data, that while a part of the gas that was formerly going to the left-hand wells is now being added to that formerly produced by the right-hand wells, actually less gas is escaping from formation now than before, and, if so, that the actual rate of depletion of the gas energy in the sand is smaller today than it was before.

I have long held a theory that every additional well drilled into an oil sand is a distinct gas liability, that it produces a larger share of the gas of the deposit than the oil of the deposit, that the more wells we drill within certain limits, the greater the wastage of gas will be. I am particularly interested in this case because apparently the data are conflicting. I, for one, should like to have more information on this point.

R. E. Somers,* Pittsburgh, Pa.—From Mr. Nickerson's standpoint and in answer to your point, Mr. Uren, he reasoned if the gas were coming through the bottom oil sands, the production of oil would also increase as the gas could not get through without adding to the oil.

A. Knapp,† Philadelphia, Pa.—I think those familiar with the old Kern River can remember that exactly the same condition occurred, except that not only gas went over but mud could be pumped over through appreciable distances from one well to another. If there are the same sand conditions in the Elk Hills that were in Kern River, there would probably be the same picture there.

R. R. Brandenthaler,‡ Bartlesville, Okla.—I think Mr. Uren's suggestion as to the sand being covered was actually so. I doubt whether the fluid level was below the top sand, knowing something about the fluid level out in that country. With the area of undrained land back of it, I rather question whether there could be drainage through the upper sand with the conditions as outlined.

C. V. Millikan,§ Tulsa, Okla.—I will venture an opinion as to an explanation for increase in gas-oil ratio. In developing new fields, I have noticed that after the first well has been completed, as a more or less general rule, the initial gas-oil ratio in later completions is larger than it was on the first well, which would indicate that probably drainage is from a considerably greater area than we commonly think of it.

V. H. Wilhelm,‖ Los Angeles, Calif. (written discussion).—The data quoted by Mr. Nickerson are valuable but I would not be willing to agree to his theory in regard to the manner of gas migration without knowing more about existing conditions in his limited area. In particular, I would doubt the vertical migration theory without exact information as to closed-in pressures, fluid levels under both shut-in and producing conditions, and if possible the pressure required to inject gas. It frequently happens that the pressure required for reinjection is very much higher than the normal fluid pressure of the well. The existence of this theory would practically preclude the vertical migration condition which is essentially reinjection.

* The Gulf Companies.

† The United Gas Improvement Co.

‡ Petroleum Engineer, U. S. Bureau of Mines.

§ Amerada Petroleum Corpn.

‖ The Texas Co.

Without definite evidence to support the theory it would seem more reasonable to explain the results by the extension of the radius of influence of the wells left on production. Under conditions of partial depletion this extension would have little, if any, effect on oil migration but would draw gas from much greater distances, the gas, naturally, coming through the more depleted zones.

C. M. Nickerson.—The writer notes that several authorities agree that the great increase in gas production for a property located in the Elk Hills oil field, as shown in Fig. 8, may be due to the increased drainage area allowed the wells continued on production. There appears to be some question as to vertical migration of the gas in the zone itself. The writer included vertical migration of gas as a possible answer to account for the enormously increased gas production, but did not intend it to be taken as the most probable solution. Vertical uniformity in the oil zone itself would not appear to be necessary to account for the observed facts.

In reply to the vertical migration theory, the picture was presented of an oil zone comprised of several individual sand strata separated by impervious strata of shale. Fluid levels in the Elk Hills oil field are very low, and in the case of the properties studied in this paper were considerably below the top of the perforations. The oil zone in the eastern end of this field is about 150 to 200 ft. thick, while the fluid levels at the present date are definitely know to be from 20 to 100 ft. from the bottom of the hole, under producing conditions. Hence the face of the upper portion of the zone must be uncovered. In an individual stratum of oil sand from 10 to 20 ft. thick in the upper portion of the zone, it would appear proper to assume that this stratum is homogeneous from top to bottom over at least an area covered by several locations. Careful coring in this field indicates that this assumption is undoubtedly correct. After this particular stratum of oil sand has been produced for several years, and the fluid levels lowered below the bottom of this stratum, the writer believe that the upper portion of this particular stratum would be found to be drained of its oil content and the voids in the sand formerly occupied by oil and gas in solution now filled with wet gas, as shown in Fig. 2. Mr. Bennett also illustrates this particular point.[1]

The wet gas in the upper portion of the individual stratum is under a certain pressure, and as production is continued, the casinghead pressure eventually will be lowered a sufficient amount to allow this gas to enter the well in increasing quantities, or rather at a faster rate. Naturally, as the gas is depleted the voids will be again filled with gas rising from the oil in the lower portion of this individual stratum, which will reach the well without carrying any oil with it. This accounts for vertical migration of gas in the individual stratum.

Vertical migration of gas from one stratum to another would ordinarily be prevented by the impervious bodies of shale lying between the several strata of oil sands, or by horizontal stratification of bedding planes in the sands themselves, but there is a definite vertical distance in each sand body through which fluids may rise. When a well is drilled through several oil-sand strata, produced for several years, and the fluid levels lowered below the top of the zone, we have an artificial vertical channel by which oil or gas may migrate vertically from one horizon to another, as occurs when a thief sand robs the well of its expected production. The writer advanced the vertical migration of gas in an individual sand stratum due to vertical uniformity in the stratum itself, and vertical migration from one zone to another permitted by the artificial channel established by drilling, as a point to be considered in a study of this type.

[1] E. O. Bennett: Effect of the Gas-lift on the Gas Factor and on Ultimate Production. Petroleum Development and Technology in 1927, A. I. M. E, 161.

The fluid levels in the shut-in wells offsetting wells continued on production has undoubtedly risen high enough by now to close off the face of the sands, but this would not prevent the gas rising through the oil in the well. In one case in the Midway-Sunset oil field a large group of wells were shut in, with fluid levels well above the top of the perforations. The operator needing gas for lease operations continued to take gas from the casinghead and even installed a vacuum line to the well to obtain wet gas. The quantities of gas obtained definitely proved that the gas was rising through the oil, leaving "dead" oil in the well and in the sands surrounding the well. This practice has been stopped since it involved an enormous waste of gas energy, with no production of oil.

In the discussion of lowered ultimate recovery due to the great increase in gas production from the group of wells indicated on Fig. 8, further study shows that for several months the gas production from the group of producing wells, following the shutdown, was about equal to the total gas production from this group and from the group of now shut-in wells for the two or three months preceding the shutdown. This would indicate that the energy of the gas production following the shutdown, while equal to that prior to this time, actually produced about one-half as much oil as would have been expected if the offset wells had not been closed in. It is true that this condition only obtained for about 21 months until gas-oil ratios returned to normal on the lease illustrated in Fig. 8, but during this time the loss in ultimate recovery of oil has been estimated at 1,000,000 bbl. This figure is a conservative one and could be easily raised to 1,500,000-bbl. loss in ultimate recovery. After Jan. 1, 1929, the actual rate of depletion of the gas energy in the reservoir was smaller than prior to Apr. 15, 1927, and less gas is now escaping from the field than when the wells of the shut-in group were producing. Further study may show that the ultimate benefits of this smaller rate of gas-energy depletion may offset the loss of 1,000,000 bbl. of oil in ultimate recovery.

The writer believes that the extension of the drainage area of wells continued on production, when the offsetting wells are shut in, is the more logical explanation of the increase in gas production for the wells classed in group 2. However, the possibility of vertical migration should be considered in a study of this type. When wells have produced from the upper portions of an oil zone for a considerable period of time, and the well later deepened to the entire thickness of the zone, the operator must consider the rock pressure of the new deeper sands, and also the present depeleted characteristics of the upper portion of the zone, if there is any possibility for the upper portion to act as a thief sand, relatively speaking. This was brought out in repressuring programs in the Buena Vista hills where gas injected into a well which had tapped only the upper portion of the zone required but a comparatively low injection pressure, while on the same lease, by using a well which had cased off the upper portion of the zone, and was open only to the lower part of the oil horizon, a much higher pressure was necessary. In the first case neighboring wells increased their gas production but repressuring had little effect on the oil recovery, while in the second case the oil production from neighboring wells was materially increased.

Means of Controlling Gas-oil Ratio

By Hallan N. Marsh* and Bruce H. Robinson,* Los Angeles, Calif.

(New York Meeting, February, 1929)

It is now generally recognized that to secure the greatest ultimate recovery of petroleum from a field it is necessary to maintain at all times the lowest possible ratio of gas to oil production. The numerous ways of securing low ratios are not so generally understood or practiced. To many operators, reduction of gas-oil ratio simply means "beaning back" wells, with resultant reduced production rate. This postponement of production is often considered and spoken of as "lost" production, with the result that control of gas-oil ratio is in disfavor with some operators.

Various methods are herein discussed by which gas-oil ratio may be reduced, some of which involve no curtailment of current production, while others are accompanied by an actual increase of daily production. It is further shown that in cases where rate of production is reduced to conserve gas, the indicated ultimate recovery is generally increased. Principles involved are discussed, and conclusions are illustrated by data from the operation of wells.

General Principles

The rate and ratio in which oil and gas enter a well are solely dependent, so far as the operation of that well is concerned, upon the pressures maintained in the well opposite the producing strata at various times and at various depths. The method of getting the oil out of the hole, whether by natural flow, gas-lift, or pumping, has no effect upon either rate of production or ultimate recovery except through its effect upon pressures.

Oil apparently enters wells according to some such equation as the following:

$$R = KC(P_f - P_w)^n$$

Where R = rate of production.

K = well coefficient, depending upon thickness of sand, and size and number of pores in the sand.

C = fluid coefficient, depending upon viscosity, surface tension, etc.

* General Petroleum Corpn. of California.

P_f = formation pressure at some point in the structure so remote from the well as not to be immediately affected by well pressure.
P_w = mean effective well pressure opposite producing strata.
n = an exponent.

This equation may also be applied to the flow of gas into a well, with suitable values of C and n. It may also be applied to the flow of either oil or gas into a well at any particular increment of depth. K is beyond the control of the operator except as it can be affected by washing, heating, deepening or other mechanical changes. C is affected by P_f and P_w, decreasing as they decrease. P_f decreases gradually during the life of the field. It may be measured by lowering a recording or maximum

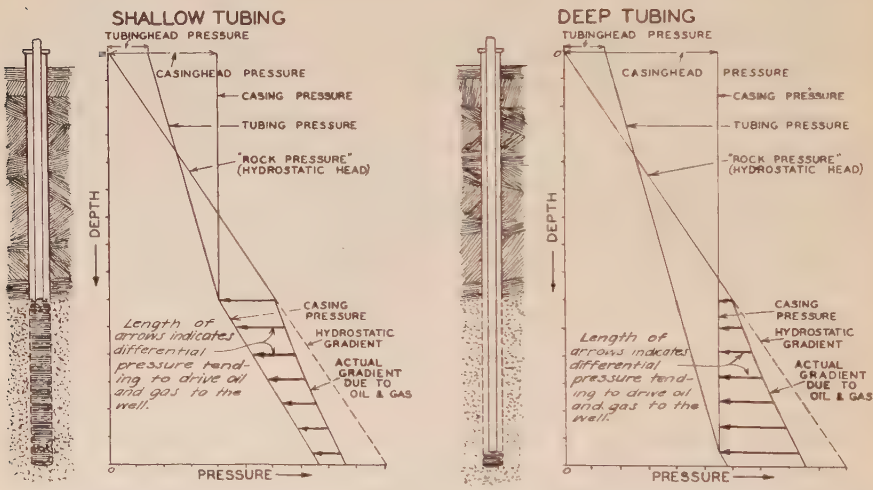

FIG. 1.—PRESSURE-DEPTH CURVES; FLOWING WELLS WITH SHALLOW TUBING AND WITH DEEP TUBING, SHOWING WHY WELLS WITH DEEP TUBING TEND TO HAVE LOWER RATIOS.

registering pressure gage to the bottom of the well after the well has been off production long enough to attain the general formation pressure. It is not necessarily equal to the casinghead pressure when a well is shut in, because there may be a fluid column in the well. It can not be reliably computed from fluid level if the fluid is at all gassy, because of unknown average density. P_w is usually unknown. If the producing zone is thin, and the well is flowing naturally through tubing, and the tubing is in or near the producing zone, P_w may be considered equal to casinghead pressure (plus weight of column of gas). This is also true with a gas-lift under the same conditions if the friction drop in the gas line is negligible or is corrected for. It is true under the same conditions in a pumping

well if the fluid level is at the pump, which it generally is not. If the producing zone is of considerable thickness, P_w is admittedly indefinite, but changes of P_w may be inferred from changes of R. An instrument to measure P_w while a well is producing would be of great value. Limited data indicate that n is about unity for oil but variable for gas. It is known to be unity for water in a water well.[1]

Due to different values of n for oil and gas, different values of P_w will result in different gas-oil ratios. Due to different values of P_f at different depths, and to the partial segregation of oil and gas at various depths, various vertical gradients of P_w will result in different values of the gas-oil ratio. The aim should be to find out at what levels the gas-oil ratio is high and at what levels it is low, and then to find a means of getting a high P_w opposite the former and a low P_w opposite the latter. It is common to find that gas is concentrated in the upper part of the producing zone, and oil in the lower part.

Fig. 1 shows the effect of tubing depth upon vertical pressure gradient.

Selective Production

Important reductions in the average gas-oil ratio of a group of wells can be made without reduction of daily production by application of what may be called selective production. This means reducing the oil production of wells where such a change is found to result in a relatively large conservation of gas, and (if desired) increasing the oil production of other wells where such increase is not accompanied by an undue increase in gas production.

It is often erroneously assumed that the ratio of gas reduction to oil reduction when a well is "pinched" will equal the previous ratio of gas production to oil production. This is only sure to be true if the well is completely shut in, in which case the ratio of reduction must equal the original ratio of production. In the case of a well which is only partially shut in, the ratios of reduction and production are not necessarily the same, and in fact are often radically different. Likewise when the production of a well is increased, the ratio of gas increase to oil increase may be either more or less than the previous ratio of production.

In order to determine which wells to restrict and which wells to open up, tentative changes must be made unless recent changes have already established ratios of reduction or of increase. In deciding which wells to "cut," inefficient results are apt to be secured if the cuts are assigned to the wells with the highest gas-oil production ratios. The following cases illustrate this.

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[1] C. S. Schlichter: Rate of Movement of Underground Waters. U. S. Geol. Surv. *Water-supply Paper* No. 140.

Well *B*-2 had a ratio of gas to oil production of 11,000 cu. ft. per bbl., which while high was not excessive considering its location. As it was desired to increase the rate of production of the lease, this well was opened up. The daily oil production only increased 40 bbl., while the gas production increased 2,000,000 cu. ft., a ratio of increase of 50,000 cu. ft. per bbl. To stop this waste of energy, the well was again restricted and previous conditions approximately restored.

On the contrary, well *B*-3*A* had such an excessive ratio of gas to oil production (22,500 cu. ft. per bbl.) that although more oil production was much desired, it was hesitantly opened up. The operator was pleasantly surprised, however, to find that this well's production could be increased in the ratio of only 6700 cu. ft. of gas per bbl. of oil, which was quite satisfactory for the particular location.

Many similar illustrations might be presented, but these two suffice to show that ratios of reduction and increase may be either greater or less than the ratio of production, by large amounts. Experience indicates that a well that has a certain ratio of reduction (or increase) at one time may be expected to have a similar ratio when another change is made within a few months, although these ratios can not be expected to check with any great accuracy, and in some cases are entirely inconsistent.

Selective production may sometimes consist of completely shutting in wells with extremely high ratios, and opening up other wells, whose ratios of increase are reasonable, enough to make up the amount shut in. For example, well *N*-10 had a ratio of 30,000 cu. ft. per bbl. It was completely shut in, and nearby wells opened up enough to maintain the production rate of the lease at its previous level. The result was a net saving of 1,000,000 cu. ft. of gas per day. Aside from eliminating the waste of this gas, keeping it in the formation resulted in a noticeable flattening in the decline curves of adjacent wells.

Deep Tubing

The use of deep tubing appears to be one of the most promising means of conserving gas without curtailment of daily production. By deep tubing is meant tubing that extends substantially deeper than the top of the producing zone. The advantage has been shown theoretically by Fig. 1, under "General Principles," and will be illustrated with data from the field.

Classifying all the wells of one company that are equipped with individual gas meters as to whether their tubing is above or below the highest perforations, it is found that the wells with deep tubing have lower average ratios than wells with shallow tubing in every field studied as follows:

Field	Average Gas-oil Ratio of Deep Tubed Wells / Average Gas-oil Ratio of Shallow Tubed Wells, Per Cent.
Athens	75
Signal Hill	52
Santa Fe Springs	72
Ventura	95

While the preceding data appear conclusive, they may be questioned, because there is a general tendency to use deeper tubing in old wells than in new wells, and old wells generally have lower ratios than new wells (barring the period of flush production). Fig. 2 shows that increasing

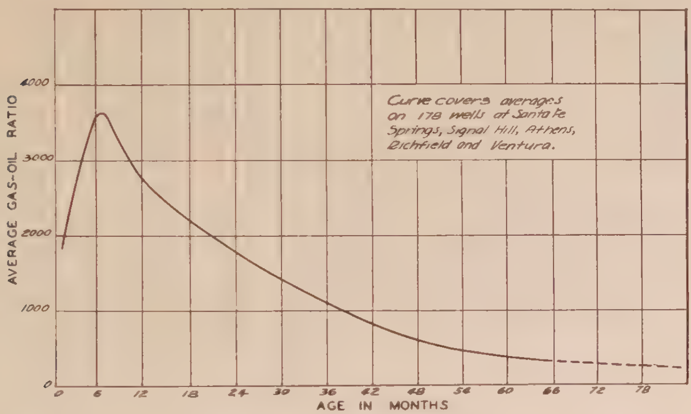

FIG. 2.—GAS-OIL RATIO; AVERAGE RATIO AT ANY AGE OF WELL.

gas-oil ratios are normal during the early life of a well, and diminishing ratios are not necessarily a proof of efficient operation during the later life. Efficiency of operation must be judged either by comparison with such an average curve, or by abrupt and prolonged changes of ratio or of the slope of the ratio curve for the particular well.

Numerous specific cases, however, confirm the conclusion that in most cases deep tubing results in lower ratios. For instance, note Fig. 3, showing the history of *B*-9. This well was flowing through drill pipe (the equivalent of tubing) from a depth of 6818 ft. There was uncased hole through producing formation from 4345 to 6818 ft. The ratio was averaging 1500 cu. ft. of gas per bbl. of oil. Incidentally this was the deepest flow string on the lease, and the lowest gas-oil ratio.

In an attempt to increase the production of the well, most of the drill pipe was fished from the hole, and the well put back on production flowing through 4712 ft. of tubing. Oil production was less than before,

gas production was more, and gas-oil ratio became about 6000 cu. ft. per bbl., four times what it had been with deep tubing. Mechanical conditions make lowering of tubing in this well impractical.

Well *S*-7 was pumping with tubing above the highest perforations, and its ratio was 3000 cu. ft. per bbl. When put on the gas-lift, the tubing was lowered 300 ft. into the producing zone, and the ratio dropped to 650 cu. ft. per bbl., or about one-fifth of what it had been.

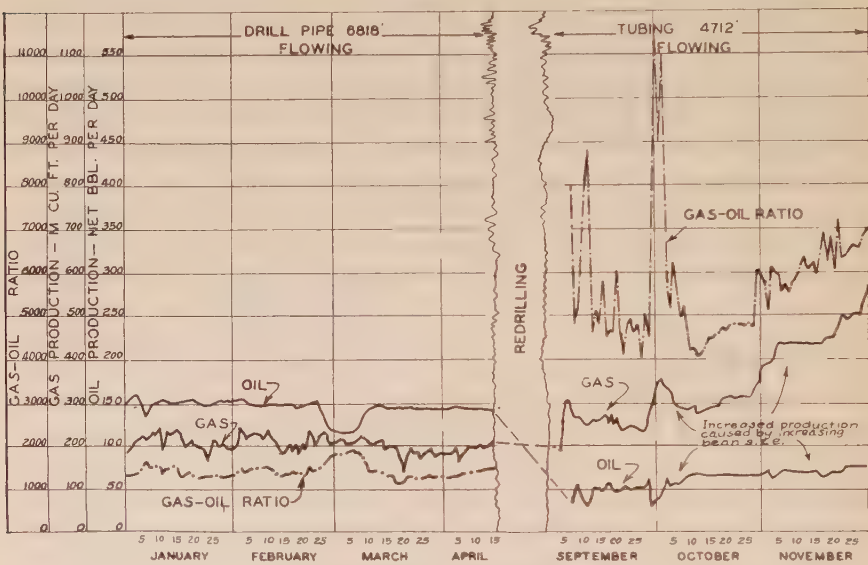

FIG. 3.—EFFECT OF DEEP TUBING.

Well *N*-5 was flowing through 3750 ft. of tubing, the highest perforations being at 3764 ft. The tubing was lowered to 4475 ft. to conserve gas, with the following results:

Tubing	Oil, Bbl. per Day	Gas, M. Cu. Ft. per Day	Ratio, Cu. Ft. per Bbl.
Shallow	111	960	8700
Deep	122	840	6900

The benefit of deep tubing is further demonstrated by Fig. 4. This well had been flowing through 4261 ft. of tubing, with a ratio of 3400 cu. ft. per bbl., the highest perforations being at 3916 ft. This ratio was not adequate to maintain natural flow, and the well died. A compressor was installed and it was found necessary to raise the tubing to 3882 ft. before the gas from the compressor would enter the tubing.

With tubing at this depth the ratio became 4000 cu. ft. per bbl., which was enough to maintain the flow without using the compressor.

This case also shows that whether or not there is tubing has no direct effect on gas-oil ratio so long as the tubing is above the highest perforations. The well mudded up in October, and was gotten back on production in November, flowing through the casing. The ratio was almost exactly the same as it had been with the shallow tubing.

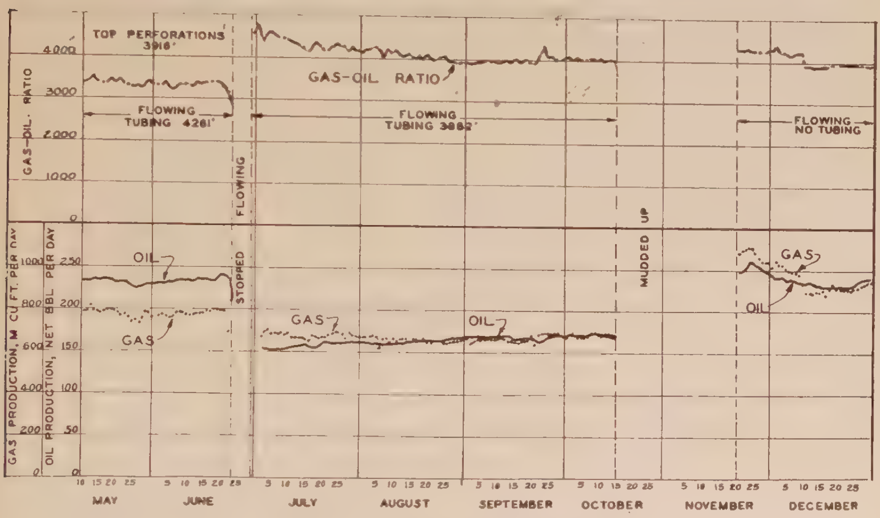

Fig. 4.—Effect of tubing.

Best Rate of Production for Any Well

Data indicate that each well has some certain mean back-pressure (corresponding to a certain rate of production) at which its gas-oil ratio will be minimum. This best rate is not the same for different wells, and may not remain the same for any well over long periods of time. It is found that some wells are producing too fast, as indicated by the fact that restricting their production lowers their ratio, while other wells are producing too slowly, as increasing their production lowers their ratio. The former is more often the case on new, flowing wells, and the latter is apt to be the case with old pumping wells where improved pump efficiency will often get out more oil with less than a proportionate increase of gas.

Fig. 5 shows the gas-oil ratio of a certain well as a function of its rate of production. This well has a practically constant ratio so long as the production remains constant. Within a period of a few months several changes in operation have resulted in several rates of production. The corresponding ratios are plotted against these rates. Each point represents an average production and ratio for at least two weeks. In no case was the tubing deeper than the highest perforations, so that the

change in ratio is primarily the effect of change in mean back-pressure as indicated by change of production rate.

New wells tend to flow at greater than their best rate, as beaning back a new well in most of the cases observed, results in reducing its gas-oil ratio. For example, well *B*-2 had a steady ratio of 15,000 cu. ft. per bbl. with a production of 110 bbl. per day. In the interest of gas conservation the back-pressure on this well was increased and the oil production rate reduced to 70 bbl. per day. This reduced the ratio to 11,000 cu. ft. per barrel.

FIG. 5.—BEST RATE OF PRODUCTION.

While the preceding case is common, it is not safe to increase the back-pressure on a well and assume that the ratio will be reduced, because just the opposite may be the case. For instance, well *B*-8 had a ratio of 7000 cu. ft. per bbl., with a production rate of 215 bbl. per day. When back-pressure was applied, and the production rate reduced to 180 bbl. per day, the gas production rate was not reduced proportionately, so that the ratio mounted to 8000 cu. ft. per barrel.

The real result of a change in back-pressure can not be safely judged by comparing the ratios immediately before and after the change. For instance, well *BD*-3 had a remarkably uniform ratio of 2500 cu. ft. per bbl. To conserve gas, it was beaned back, with a slight reduction of production rate. Surprising as it may seem there was no change in ratio for 12 days, but at the end of this time the ratio dropped to 1600 cu. ft. per bbl., at which level it continued quite steadily. As no other changes were made, this drop in ratio, although delayed, must be attributed to the increased back-pressure.

In many cases, an increase in back-pressure makes no immediate change in ratio, but a day-by-day graph of the ratio will show that the ratio had been steadily increasing up to the time of the change, and then either stopped climbing, or actually started falling off. Such a change may be just as valuable or more so than an abrupt drop in ratio after

which the curve resumes its previous slope. Only by allowing plenty of time for a change in operation to take effect, and then studying a complete day-by-day chart of oil production, gas production, and gas-oil ratio, can the wisdom of that change be judged.

The gas production of some wells, especially old wells, is very little affected by changes in back-pressure, so that the installation of more efficient pumping equipment may result in substantial increases in oil production without proportional increases in gas. For instance, the gas-oil ratio of well *A*-53 varies inversely with oil production. The average production is about 100 bbl. per day and the average ratio

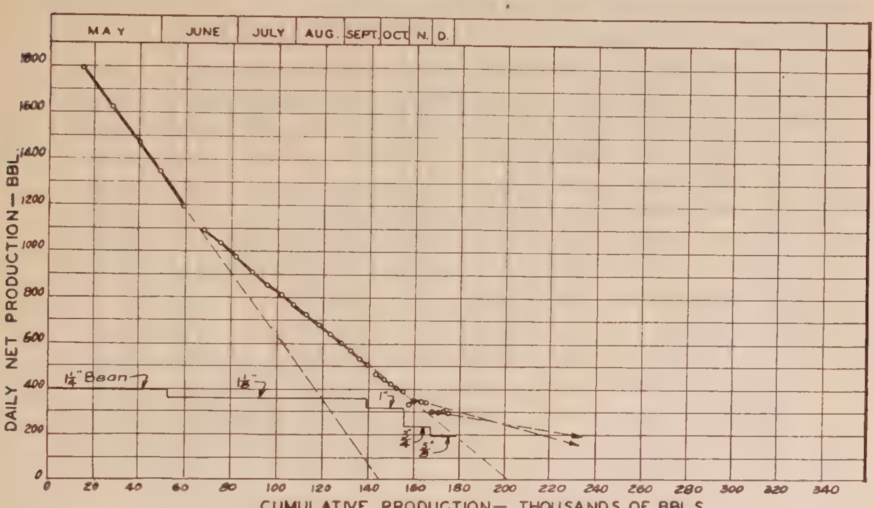

FIG. 6.—INCREASING BACK-PRESSURE RESULTS IN INCREASED ULTIMATE RECOVERY.

about 600 cu. ft. per bbl. When the pump becomes worn and the production drops to 80 bbl. per day, the ratio mounts to 700 cu. ft. per bbl., and when a new pump brings the oil production up to 160 bbl. per day, the ratio drops to 400 cu. ft. per bbl. With wells of this character, every effort should be made to keep the production rate as high as possible, because the resulting low ratio can be expected to lead to high ultimate recovery as well as high daily production.

When it is found necessary to increase back-pressure to conserve gas, it is reassuring to know that the change is apt to result in substantial increases in indicated ultimate recovery, as illustrated by Fig. 6.[2]

CASING PRESSURE ON PUMPING WELLS

Deep tubing is only beneficial to the extent that it results in small average pressure gradient in the well from top to bottom of the producing

[2] For discussion of this form of chart, see H. N. Marsh: Methods for Appraising Results of Production Control of Oil Wells. Amer. Petr. Inst. (1928).

zone. Below the fluid level, the gradient is steep, corresponding to the density of the fluid. Above the fluid level the gradient is almost zero, corresponding to only the density of the gas. The aim, therefore, should be to get the fluid level as low as possible, and then apply whatever back-pressure is desired with a gas pressure maintained on the casing.

If maximum production rate is desired, this casing pressure will be atmospheric, or may even be a vacuum. Experiments with the use of vacuum, however, have shown that application of vacuum to the casing of wells with deep tubing may result in increased rate of production, but generally causes serious increase of gas-oil ratio. It may be inferred from this that use of positive pressure on casings of such wells would result in reduced ratios.

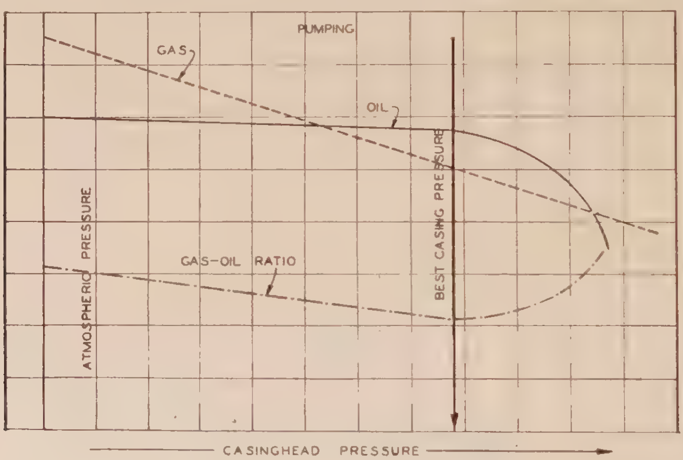

FIG. 7.—EFFECT OF CASING PRESSURE ON WELLS WITH DEEP TUBING.

The experience of one company indicates the general relation shown by Fig. 7 for pumping wells with deep tubing. As the casing pressure is increased, the gas production declines steadily over the whole range of the experiments, but the oil production declines only slightly until a critical pressure is reached, after which it drops suddenly. The result is that the ratio has a minimum value at this critical pressure, rising on either side of it. Experiments by Swigart and Bopp[3] lead to the same conclusions.

These observations fit in perfectly with theory. It is believed that at casing pressures below the critical the fluid level is above the pump, and as the pressure is increased the fluid level is correspondingly lowered. Pressures below the pump, where most of the oil is entering, remain

[3] T. E. Swigart and C. R. Bopp: Experiments in the Use of Back Pressure on Oil Wells. U. S. Bur. Mines *Tech. Paper* No. 322 (1924).

almost constant, with resulting constant oil production, while pressures above the pump, where most of the gas is entering, increase. Further pressure increases, after the fluid level is depressed to the pump, cause gas to enter the pump, with resultant loss of volumetric efficiency and drop in oil production.

The aim should be to operate such wells with a casing pressure slightly less than the critical. Completely shutting in the casing will force the gas into the pump with resultant loss of capacity. Manual regulation can not be expected to give satisfactory results. What is needed is an adjustable back-pressure regulating valve.

Steady or Intermittent Production

The way in which back-pressures vary from minute to minute has a very important bearing on the gas-oil ratios of some wells. The experience of one company in California shows that intermittent operation

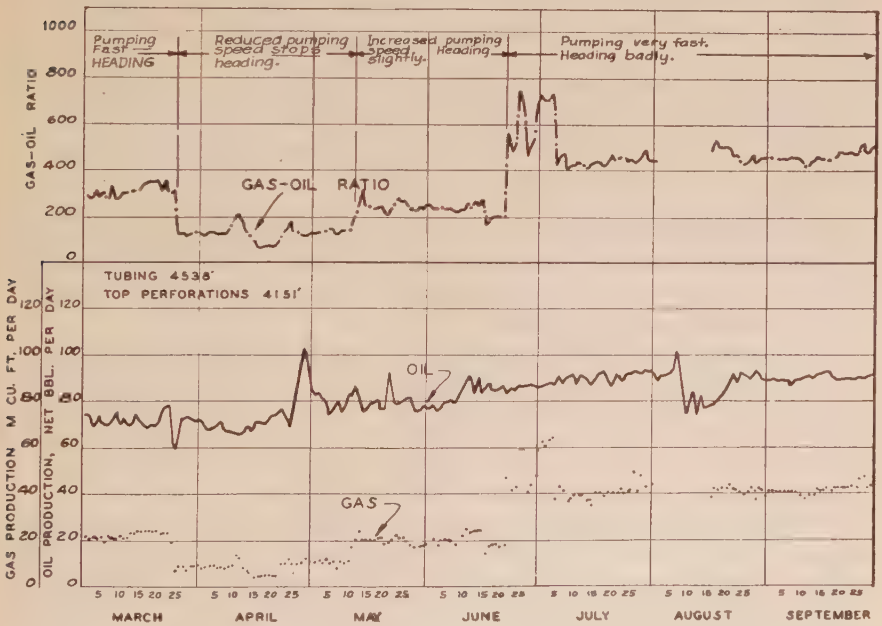

Fig. 8.—Reduced pumping speed stops heading.

of gas-lifts gives different results on different wells. The ratios of some wells are substantially increased by intermittent operation, while those of others are substantially decreased, and others are unchanged.

Experiments by the writers for an entirely different purpose accidentally provided interesting data on this subject. In order to save power, and reduce maintenance on equipment, the pumping speed of

well *S*-43 was reduced from 24 to 16 strokes per min. There was no substantial change in oil production rate, but the well which had previously been producing intermittently due to "pumping off" and "heading," produced steadily, with the result that the gas-oil ratio dropped to one-third of what it had been. (Fig. 8.) In later attempts to increase production rate the well was progressively speeded up, with corresponding reversions to heading and high ratio.

Morgan Walker[4] reports that intermittent operation of gas-lifts results in higher net gas-oil ratios, as shown by the following data quoted from his paper.

Well	Net Gas-oil Ratio, Cu. Ft. per Bbl.	
	Continuous Flow	Intermittent Flow
Anderson 2	228	773
Cowden 4	207	613
Nitoy 3	65	232
Nitoy 2	292	282
Fixico 3	75	1660
Routie 3	514	745
Killingsworth 3	367	932
Cowden 3	391	2180

These data are tentatively accepted not only because of the absence of published conflicting data, but because they so nicely explain the accepted fact that intermittent operation of gas-lifts requires less circulated gas than steady operation.

The effect of intermittent production (variable back-pressure) is not well understood from a theoretical standpoint, and experimental data are very meager. The subject is of enough importance to warrant research.

Negative Gas-oil Ratio

While really a special case of the use of deep tubing, the subject of negative gas-oil ratio is of sufficient importance to merit separate discussion. Negative net gas-oil ratio can be secured in some cases by operating a gas-lift or pumping well in such a way that more gas is pumped into the well with the compressor than comes out. This may be considered as repressuring or gas injection, with the same well used simultaneously for injecting gas and producing oil.

Referring to Fig. 1, the theoretical possibility of negative ratios may be seen. If, in the right-hand figure, showing pressure relations for deep tubing, the casing pressure be sufficiently increased, the line repre-

[4] M. Walker: Intermittent Injection of Gas in Gas-lift Installations. See page 151.

senting that pressure will be moved to the right until it intersects the line marked "actual gradient (in structure) due to oil and gas." The arrows or vectors representing differential pressure will then point to the right or away from the well in the upper part of the (previously) producing zone, and to the left, or toward the well in the lower part of the zone. This means that with the fluid level at or below the level of zero differential (where the direction of the vectors reverses) there will be gas flowing out of the well into the structure above the level of zero differential, and oil and gas entering the hole near the bottom. If pressures are correctly adjusted, the outflow of gas may be greater than the inflow, and the inflow of oil greater than the outflow (if any).

This condition was attained in well *S*-5 with the gas-lift. The highest perforations are at 3715 ft. With tubing at 3701 ft., the net gas-oil ratio was +370 cu. ft. per bbl. Tubing was lowered to 3753 ft., which resulted in lowering the net ratio to almost exactly zero. Tubing was further lowered to 3791 ft., and gas-oil ratio dropped to −275 cu. ft. per bbl.

Acknowledgments

The writers are indebted to the executives of the General Petroleum Corpn. for approval to prepare and publish this paper. So many excellent articles have been written on the general topic of ultimate recovery and gas-oil ratio that even a list of all those from which ideas or supporting data have been drawn would be unduly long. They are, however, gratefully acknowledged.

Back-pressure Control of Flowing Wells*

By H. C. Miller,† San Francisco, Calif.

(New York Meeting, February, 1929)

The energy stored in the compressed natural gas absorbed in or otherwise associated with the oil in reservoir sands is usually the most important factor in oil recovery. It is recognized that hydrostatic pressure and gravity may aid materially in the drainage of oil, but in the early life of the majority of fields the principal source of propulsive energy is the expansive force of the gas associated with the oil. Since gas is admittedly the most important factor in the production of oil, its control so as to produce the maximum amount of oil with the minimum amount of gas will be reflected in increased oil recovery from reservoir sands. Controlling the gas means regulating its expansion so that the velocity of flow of oil through the channels in the reservoir sands is neither so great that frictional resistance becomes excessive nor so slow that the gas, because it can travel more rapidly than oil through the irregular passageways in the sands, will by-pass and reach the well without doing useful work in bringing oil from the sands.

Oil and gas flow from the reservoir sands to the well because of differences in pressure. The rate of flow is dependent upon the differential pressures existing in the sands and in the well. By altering the amount of back-pressure maintained on the well this differential pressure can be regulated and changed from a maximum (well flowing "wide open") to a minimum when there will be no flow. Oil and gas flow through the irregular channels in reservoir sands at different rates mainly because of the fact that one is a liquid and the other a gas. Therefore, because oil and gas have different characteristics of flow, application of back-pressure changes the rates of flow with relation to one another so that wide variations in gas-oil ratios are possible. Obviously, the formation gas energy will be utilized most efficiently when a unit of gas delivers the maximum amount of oil to the well.

Determination of Necessary Back-pressure

The amount of back-pressure that should be maintained against the producing sand in order that the minimum amount of gas will be produced with each barrel of oil can be determined only by actual field tests made

* Presented by permission of the Director, U. S. Bureau of Mines.

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on the individual wells. Information concerning natural conditions such as formation pressure, permeability of the producing formation, nature of the oil produced, and the relative volumes of gas to oil and the nature of their association in the sand originally, is also valuable and will aid the engineer in determining the proper amount of back-pressure to hold against the producing formation. Underground conditions vary from well to well and from time to time in the same well, and no two wells are exactly alike in all details. Therefore, back-pressure control of flowing wells is a problem that requires experimentation on individual wells. Although well characteristics vary and conditions are never exactly alike in any two wells, sufficient field data, augmented by experimental data in the laboratory, have been obtained to indicate that wells which penetrate sand more or less alike in porosity and degree of saturation and which have similar characteristics of depth, pressure, and amount of production respond similarly to back-pressure regulation.

The extremely highback-pressures that may be carried on large flowing wells during their early life, and the relatively small amount of gas that accompanies each barrel of oil to surface, show that very little energy is required to move oil short distances through reservoir sands when pressures are high. This may be accounted for in two ways: (1) under high back-pressures a considerable proportion of the formation gas is maintained in solution in the oil, and (2) the growth of gas bubbles in the reservoir sand pores is retarded and very little energy is required to deform the small gas bubbles as they flow with the oil through the irregular pore spaces in the sand. If the differential pressure at the face of the sand is increased materially, that is, if the back-pressure is reduced, gas comes out of solution and increases the viscosity of the oil. The gas thus released fills spaces in the sand, blocks the passageways to the flow of oil, and increases the forces required to produce a given flow of oil through the narrow pores in the reservoir sands. Efficient flow, therefore, during the early life of a well demands back-pressure approaching in force the pressure existing in the reservoir.

Proper back-pressure control is also a means of controlling the encroachment of edge water; in many wells bottom water will "cone up" and prevent the oil from reaching the well unless back-pressure is maintained.

Effect of Back-pressure Control on Gas-oil Ratios

The results of the application of back-pressure methods manifest themselves in changes in rates of production of oil and gas. The influence of such methods on recovery efficiencies is indicated by changes in the gas-oil ratio and more particularly in the trend of the gas-oil ratio curve.

The consensus of opinion among production engineers is that there is a certain back-pressure, commonly known as the optimum back-pressure, at which the formation gas-oil ratio is the minimum. A back-pressure in excess of this optimum pressure will sometimes increase the gas-oil ratio because too much reduction in velocity of flow of oil and gas through reservoir sands will cause increased slippage and by-passing of gas in the spaces between the sand grains. Too high a back-pressure may be uneconomical also, because the rate of oil recovery will be too low, and if adjacent wells are allowed to produce at a lower pressure, oil may be driven to the offset wells. Optimum back-pressure can be determined only by balancing physical factors against others that are largely economic. Obviously an economic rate of production is desired, but often this rate does not allow utilization of the energy of the formation gas to the fullest extent. This condition is true especially in small flowing wells. Wells of large production, however, will usually flow at an economical rate when very high back-pressures are held against the producing sand. Moreover, the recovery rate is generally an efficient one, as is indicated by the low gas-oil ratios of many large flowing wells under back-pressure control.

Effect of Back-pressure Control on Efficiency of Production

In general, operators are prone to carry too little back-pressures on their flowing wells to produce them efficiently. It is usually a short-sighted policy to consider current production only and to disregard ultimate recovery, but nevertheless many operators follow such a practice. Although no one can predict what the future may have in store for the oil industry, it is certain that if every operator would practice gas conservation and produce his flowing wells efficiently, overproduction of oil would be a thing of the past, and the country's ultimate recovery of oil would be greater than if back-pressure control had not been practiced. Even at a reduced rate of production, operators would be able to produce their oil at a profit commensurate with the financial hazards incident to finding and producing their oil. The monetary losses due to deferred production are temporary losses that are soon recovered and made up many times over by the elimination of above-ground storage costs for tankage, insurance, interest on investment, and evaporation losses. Excessive expenditures for equipment to handle flush production would also be eliminated. Furthermore, by controlling flush production in new fields, the downward fluctuations in crude oil prices which occur when flush production from a new field floods the market would be eliminated. In addition, since back-pressure control extends the flowing life of wells, greater profits will accrue from production; lifting costs are less if wells flow naturally than if artificial producing methods are used to bring the oil to the surface.

Certain outstanding facts regarding back-pressure control have been determined by making tests on many flowing wells, and the following major conclusions have been reached:

1. Back-pressure control may be applied by several different methods. The use of flow beans is the most important and widely used.
2. It is successful in reducing gas-oil ratios and therefore increases ultimate recovery from reservoir sands.
3. It is more effective if applied early in the producing life of wells.
4. It may or may not decrease current oil production, although the preponderance of data show that daily production is usually reduced slightly when back-pressures are applied.

Production data obtained from wells under back-pressure control compared with similar data from wells that produced without such control show that at the end of a relatively short time, sometimes less than six months and rarely more than a year, the wells under back-pressure control have a higher average daily production and that their cumulative return will be greater than wells which are allowed to flow against no back-pressure. Back-pressure control also conserves gas, stabilizes gasoline production, and prevents overproduction of oil. No matter from what angle back-pressure control is viewed, it is a conservation measure of paramount importance and one that should be applied in every oil field where gas pressure is the chief factor in oil production.

Graphical Data Important

Two factors are recognized to be of vital importance and essential to the successful experimentation of back-pressure methods on flowing wells. Merely lowering a gas-oil ratio by changing the amount of back-pressure on a well does not necessarily imply that the change is beneficial. The trend of the gas-oil ratio curve subsequent to a change in back-pressure is the most important item from which conclusions are drawn. Therefore, it is most important to record, preferably in graphic form, oil and gas production, gas-oil ratio, and pressure data. The second important factor of successful experimentation is the making of only one operating change at a time, allowing the well to produce for a sufficient period between changes—perhaps as long as 2 or 3 weeks—in order that conditions may adjust themselves and that the definite trends of the new gas-oil ratio curve may be determined. Without statistical data and information which reflect conditions at the well in true perspective, conclusive results can not be determined and subsequent changes in well operation must be made blindly.

Flow-bean Control

Generally the most successful method of applying back-pressure on flowing wells is by means of flow beans inserted in the lead lines from

wells. Flow beans are used successfully in wells where the flow is through tubing or casing. In either case the beans impart a restriction to the flow of oil from the well so that an added pressure is exerted against the face of the producing formation.

Flow beans may be of the solid type consisting of a cylindrical section of steel from 3 to 5 in. long, through the center of which a hole has been drilled longitudinally, or they may be of the adjustable type. The diameters of openings in the solid type of flow bean vary usually by sixty-fourths of an inch from $\frac{1}{8}$-in. to $1\frac{3}{4}$-in. size, or larger. Changes in size of flow-bean opening necessitate changing the flow beans. This is a relatively simple and quick operation when well-head connections are arranged so that the flow of oil may be diverted through any one of two or more lead lines.

The use of adjustable flow beans is rapidly becoming more general because of the ease with which changes in the size of flow opening can be made and the fact that such changes can be made without interfering with the flow of oil from the well or diverting it through other lead lines.

When a flowing well is completed, the rate of flow of the well is regulated by changing flow-bean sizes until the well flows steadily and at a constant pressure. Subsequent bean changes should then be made gradually, allowing sufficient time to elapse between changes to gain an idea of the trend of the gas-oil ratio curve. Often a change in size of bean opening will result in a pronounced difference in gas-oil ratio. If this change increases the gas-oil ratio, the operator may be led to believe that it was harmful. However, if no further change is made for a week or two, subsequent data may show that the previous upward trend of the gas-oil ratios was broken. Any flattening out or decline in gas-oil ratio curves mean greater recovery efficiency. Even a pronouncedly lower gas-oil ratio, following a change in the size of flow-bean opening, is not necessarily an indication of increased recovery efficiency unless the new trend of the gas-oil ratio curve is flatter than formerly.

No more outstanding example of gas conservation and consequent increase in recovery efficiency can be cited than that accomplished in the Ventura field in California. The production of vast quantities of gas for which there was no market compelled operators in that field to bean flowing wells drastically in an endeavor to curtail waste of gas and increase the recovery efficiency of oil. Swigart[1] sums up the results of the work done in the Ventura field by stating:

"A review of individual well production graphs of large flowing wells developed the fact that a close relation apparently existed between the trend of oil production of large flowing wells and their gas-oil ratios. It was learned that so long as daily oil production of high-pressure flowing

[1] T. E. Sweigart: Methods of Effecting Gas Conservation and Increased Recovery Efficiency in Ventura Field, California. A. P. I. *Bull.* 262 (1928) 66.

wells is declining, gas-oil ratios are usually increasing, and if oil production increases due perhaps to drastic beaning, gas-oil ratios decrease. The relation is so marked that it is found in most cases that if oil production maintains a level rate, gas-oil ratios also maintain a level rate and neither increase nor decrease. It seems probable that the critical back-pressure for such wells, that is, the operating pressure that gives the best recovery efficiency, is one which results in an oil production at slightly increasing or constant rate."

Although back-pressure control of flowing wells is most frequently applied by means of flow beans, other methods, such as altering the size and depth of tubing and holding pressure on the gas and oil separators, are at times effective.

Controlling Back-pressures by Altering Size and Depth of Tubing

Controlling back-pressures by altering the size and depth of tubing is more difficult to accomplish and usually less effective than the use of flow beans. As it is desirable to flow wells through one size of tubing as long as possible, and since the average pressure drop in 2½ and 3-in. tubing varies from about 4 to 8 or 10 lb. per 100 ft. of length, it is apparent that the average size of tubing generally used will not alone impose sufficient back-pressure on high-pressure producing sands to help greatly in controlling the expansion of formation gas and cause efficient flow of oil to the well.

Although 2½ and 3-in. tubing are installed in wells flowing several thousand barrels a day, such tubing may be too small in new wells when production is high and too large after production has declined. However, inefficient tubing flow of small consequence during the flush-production stage, because high back-pressures are needed at the bottom of the tubing during that period of flow. The fact that tubing is too small during the flush production period and friction losses are high is an advantage rather than a detriment to back-pressure control of large flowing wells.

Changes in back-pressure resulting from altering the depth of tubing in large flowing wells seldom have a material effect on gas-oil ratios, because the friction losses per 100 ft. of flow line for average sizes of tubing are not very great. Since it is difficult and often unsafe to alter the tubing depth in high-pressure flowing wells, the tubing should be installed at the inception of the well's flowing life to a depth that will give the greatest average flowing efficiency throughout the period to the time that it is practical to change the tubing depth. The location of the bottom of the tubing in large flowing wells is generally not important. Such wells will flow satisfactorily when tubed to a point above the producing sand or anywhere opposite the sand. However, when the period of flush production is past, satisfactory flow from these same wells may

be obtained only when they are tubed below the top of the producing sand. Therefore where there is no danger that the oil string will collapse —and in general this danger exists only in California and Gulf Coast areas where long strings of perforated pipe are set through thick oil zones - large flowing wells should be tubed to a point below the top of the producing sand at the beginning of their flowing life. Comparative data on certain wells show that large flowing wells have lower gas-oil ratios and flow for a longer period at a more sustained rate if tubed close to the bottom of the well.

Although the use of tapered tubing is thought by some engineers to be beneficial in flowing wells, the writer does not believe that the use of such strings is helpful during the early life of high-pressure flowing wells. A uniform size of tubing imparts greater friction to the rising fluid and therefore aids in placing back-pressure on the face of the producing sand. Later in the life of a well when the most efficient differential pressure at the face of the sand is one requiring a lower back-pressure than that imposed by tubing of uniform size, then tapered tubing by reason of reduced friction may be advantageous in affording a means of operating at lower working pressures, and its use may result in increased production and greater flowing and recovery efficiencies.

As a well grows older, the distance which oil has to travel through the reservoir sands to reach the well increases, and a constantly increasing expenditure of gas energy is required to keep oil moving to the point of lowest pressure, which is the well. In addition, the bubble resistance (Jamin effect) becomes greater as wells grow older, and as a result more gas energy must be expended to overcome the increasingly greater gas-bubble resistance if the flow of oil is to be maintained. Although changes in operating methods at oil wells may cause temporary level or downward trends in gas-oil ratio curves, it is recognized that if the entire life of a well is considered, the general trend of the gas-oil ratio curve is upward. Maximum recovery of oil from the reservoir sand is a result, therefore, of operating a well in such a way that the average rate of increase of gas-oil ratio is a minimum. This can be accomplished by giving strict attention to the amount of back-pressure held against the producing sand; the back-pressure obviously must gradually be reduced as the formation pressure becomes less, for, as previously mentioned, oil flows to the well mainly because of differences between pressures existing in the formation and in the well.

Rate of Return of Deferred Production

Although pressure control of flowing wells usually decreases daily oil production, the percentage decrease of daily production in almost every instance is less than the percentage decrease in gas-oil ratios, indicating that more often than not ultimate recovery will be greater

if pressure control is applied. Since daily production is usually less when wells are produced under back-pressure control, and since production is consequently deferred, a considerable amount of opposition to the practice has arisen among certain operators and has led them to believe that back-pressure control is not economically sound.

Available data indicate that deferred production when considered in terms of the life of a well is returned in a comparatively short time. It may be six months, a year, or longer but on the average the period of waiting for return of deferred production is short enough to dispel all opposition to back-pressure control of flowing wells. Furthermore, production graphs show that when pressure-controlled wells and wells not operated under pressure control reach the point where their cumulative productions are equal, the pressure-controlled wells usually have the higher daily rate of oil production. These results indicate that ultimate recovery will be greater from wells operated under pressure control.

Cooperation Necessary for Efficient Back-pressure Control

Since oil and gas are mobile substances, accumulated in reservoirs from which the escape of gas usually is possible only through the wells, the inefficient utilization or waste of gas from any well in the common source of supply will affect to a degree the total recovery from the reservoir as a whole. Inefficient operation even of one well on a lease will affect to a greater or less degree the ultimate recovery of oil from that lease as well as from the entire reservoir. Furthermore, all properties surrounding a lease on which one or more wells are operated inefficiently will be affected adversely. The degree of harmful effect depends mainly upon the degree of inefficient utilization of gas on the one property and the amount of back-pressure held on the surrounding leases.

Since the majority of reservoirs of oil and gas are controlled by more than one operator, each desirous of recovering as much oil as possible, back-pressure control, because it usually decreases daily oil production, works undue disadvantage on any operator producing from that reservoir who singly desires to operate his wells efficiently. Cooperation of all operators in a field is necessary and essential to efficient operation of back-pressure control of oil wells. For maximum results, this cooperation may at times compel the drastic "pinching in" of wells with high gas-oil ratios. Sometimes wells must be shut in completely if their gas-oil ratios with respect to the average is still so high that inefficient flow continues after every means of correction has been exhausted. Operators are justified in conserving the common source of supply of formation gas no matter how drastic may be the means of attaining efficient flowing conditions, and in the end all operators on a single structure will profit by producing their wells in accordance with sound engineering practices.

Conclusion

No mention has been made of the application of back-pressure control to wells other than those which flow naturally. Because this phase of back-pressure control has been omitted, it should not be implied that such control is ineffective and nonproductive of good results on gas-lift and pumping wells. Back-pressure may be adjusted and maintained on gas-lift wells as in flowing wells. In addition, it is possible to vary the amount of back-pressure in gas-lift wells over wide limits by changing the volume of circulated gas. The effective back-pressure on the face of the producing sand in pumping wells may also be controlled by a method similar to that used in flowing wells. Varying the speed and length of stroke of the pump are additional methods of effecting changes in back-pressures on pumping wells.

The conservation of gas and the economic production of oil should be practiced throughout the life of a well. The efficient application of proved principles and methods of gas conservation to field and lease operation and also to that of individual wells is a means of increasing ultimate recovery of a mineral that even in this day of overproduction is too valuable a natural resource to waste or to leave underground where it can not be recovered by present methods of production.

The application of pressure control on oil wells to conserve the energy in the formation gas so that it will bring the maximum amount of oil to the well is unquestionably of paramount importance in oil recovery. The petroleum industry is recognizing more and more the value of gas as a factor in oil recovery, and every one engaged in oil production should be untiring in his efforts to bring about the application of pressure control on all wells where gas is the propulsive agent.

DISCUSSION

C. W. Hamilton,* New York, N. Y.—What experience has there been in the States in placing the bean or choke in the tubing in the well, and what results have been obtained as compared to placing the bean in the well connections?

H. C. Miller.—It has always been my impression that the proper place to tube a well was in the bottom, and I endeavored to gather some data on such practice. I found there was always "something the matter with the well" when the flow bean was placed at the bottom of the hole, so the data obtained were of no value.

The first thing we had to contend with was the solid-type flow bean. It was impossible to know what size bean would be needed at the bottom of the well, and running a string of tubing to find out meant too much shutdown time.

The Shaffer people now manufacture an adjustable-type flow bean, which is attached to the bottom of the tubing. The tubing is suspended at the casinghead by swivel connections, so the size of the bean opening can be varied by turning the tubing on the derrick floor. I understand that some good results were obtained in a few

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* Assistant to Vice President, Venezuela Gulf Oil Co. and South America Gulf Oil Co.

wells, but they were not conclusive. I believe that we should perform more experiments on beaning wells at the bottom of the tubing.

C. W. Hamilton.—Mr. Miller might be interested in knowing that this experiment was tried in Venezuela by one of the operating companies. The experiment was not conclusive, as it was conducted on only a few wells. The result, however, was very discouraging. The same size bean was used in the tubing as had been used on the well connections. Production decreased. There was more of a surging effect in the flow, and the beans when pulled out were badly sand-cut, whereas those in the well connections were very little affected by the sand.

H. C. Miller.—It seems to me the flow bean at the bottom should be much smaller than at the top, because the gas volume is much less. It may be that with a smaller bean the results might have been better.

It is difficult to put a flow bean at the bottom of the tubing, and before that, to get the production men in the field to allow you to do it. They dislike having their wells shut down for any reason other than something for which they may be responsible and for that reason the engineers in the field have trouble in experimenting long enough on any one well to get really conclusive results.

E. L. Estabrook,* New York, N. Y.—We tried putting the bean on the bottom of the tubing at Salt Creek six or eight years ago, and as far as we were able to find out, there was no positive result in improving either the gas-oil ratio or the production.

L. C. Uren,† Berkeley, Calif.—From the theoretical aspects of the subject, it would seem to be highly desirable to have the bean at the bottom of the flow tubing, for the reason that the gas as discharged at the tubing head is then at atmospheric pressure. If the bean is placed at the tubing head, the gas is necessarily discharged under elevated pressure so there is a definite energy loss that is being sacrificed in the system, energy put to no useful purpose.

I happen to know of a few experiments along this line in the Los Angeles Basin, where no very advantageous results were secured, corroborating the statement of Mr. Estabrook. The added difficulty of replacing the flow bean, when necessitated by wear, made it practically disadvantageous.

R. R. Brandenthaler,‡ Bartlesville, Okla.—I know of two instances, one on the West Coast during 1924, and one in the Seminole area at the present time, where bottom-hole beaning proved successful. On the West Coast, a company operating in the Santa Fe Springs field obtained some very satisfactory results. It is my understanding that they used smaller flow nipples than those ordinarily used at the well head. Two wells in the town-lot area continued on natural flow and maintained a high daily production, with offset wells on the pump.

In the Seminole area one company has been flowing several wells using a special type of bottom-hole flow bean having a $\frac{9}{64}$-in. orifice. This is rather surprising in view of the fact that offset wells have been on the pump for several months, in some instances over a year. The size of bean is determined mathematically from the lift, formation pressure and volume of oil to be raised.

With reference to the effect of tubing wells near bottom, we had tubed 27 wells and flowed them by applying pressure control, in one of the Oklahoma pools. When the wells were tubed to below the top of the sand, paraffining of the tubing resulted in a surprisingly short time, in one case in approximately two weeks, whereas when

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wells were tubed above the sand and a back-pressure was maintained on the tubing at the well head, no paraffining resulted. This led us to believe that tubing a well low in the Mid-Continent was not advantageous. Also, many of the wells would not flow when tubed too low.

It has been said that it is not good practice to hold pressure on wells on one property when wells on offset properties are producing without back-pressure. That is true when producing from a coarse-textured formation. However, in the example cited, the wells produced under pressure control have shown a greater recovery to date than that obtained on offset leases.

Analyses of Waters of the Salt Creek Field Applied to Underground Problems*

By J. S. Ross† and E. A. Swedenborg,‡ Midwest, Wyoming

(New York Meeting, February, 1929)

Oil-field waters enter into many underground problems with which the petroleum engineer has to deal. Whether the problem is one of infiltration or natural encroachment, it is always desirable to determine the source of the water before commencing repair or remedial work. The usual mechanical tests for determining the source of extraneous water in wells are slow and expensive. An excellent means for the identification of oil-field waters may be afforded by their chemical characteristics when the chemical character of waters from the various sands has been established by careful sampling and analysis cautiously interpreted.

In the Salt Creek field, Wyoming, a fairly high degree of efficiency has been attained in the control of field operations by utilizing the information afforded by the analysis. All of the operating companies appreciate this means of identifying waters, with the result that water-sampling has become general practice. Most of the chemical work dealing with Salt Creek waters has been done since the laboratories of the Midwest Refining Co. and the U. S. Geological Survey, were established in the field; the former in 1922, the latter in 1924. A spirit of cooperation has existed between the company and the government personnel by which many of the data for this paper were made available.

Sands of the Salt Creek Field

The principal sand horizons in the Salt Creek field are the Shannon, First, Second, and Third Wall Creeks, Dakota, Lakota, Sundance and Tensleep. Of these the important oil producers are the First Wall Creek, Second Wall Creek, Lakota and the Sundance. The Third Wall Creek is lenticular and is productive in only a few wells in the southern end of the field. There are also a number of shale wells, but they do not produce water in any appreciable amount.

The stratigraphic position of these sands and their relative thicknesses are shown on the condensed composite section of Salt Creek

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† Petroleum Engineer, U. S. Geological Survey.

‡ Assistant Chemist, U. S. Geological Survey.

formations which appears on the right of Fig. 1. The approximate limits of oil in the First and Second Wall Creek sands are also shown

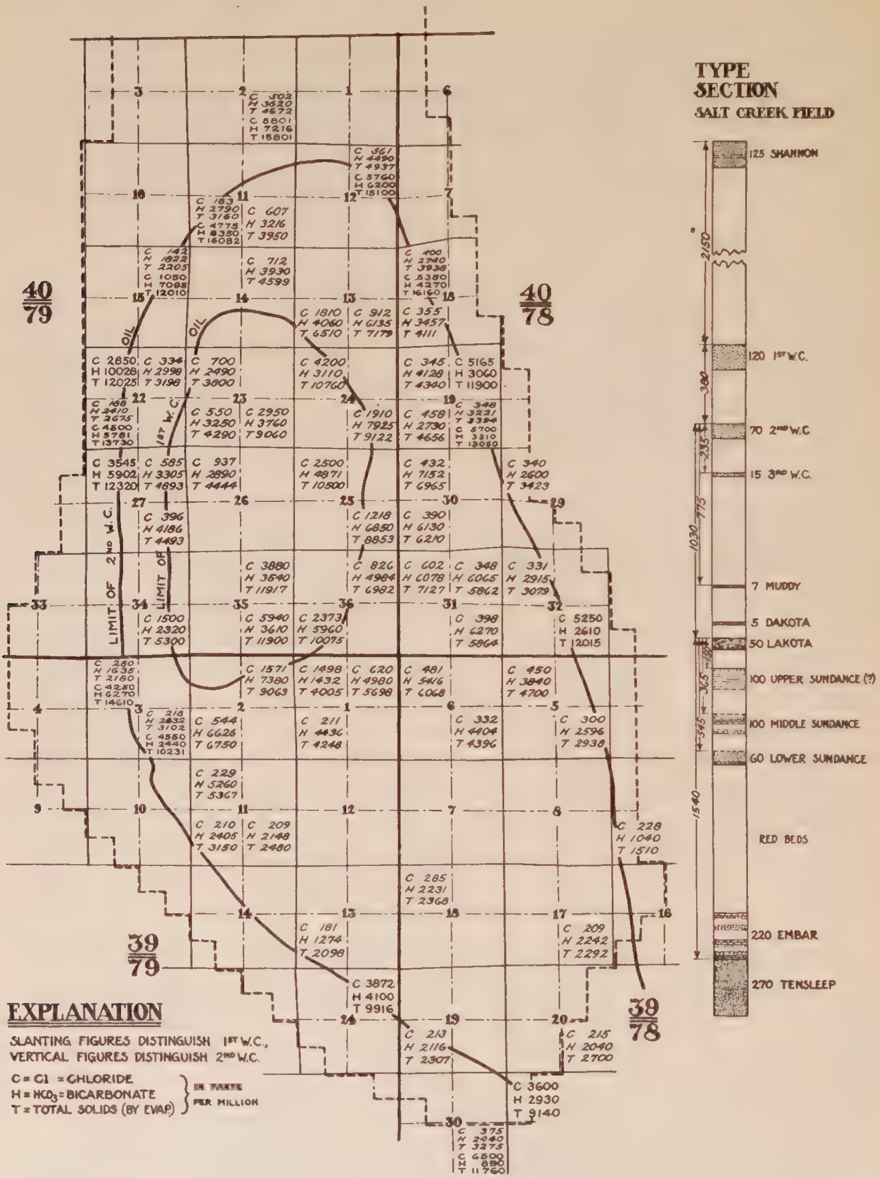

Fig. 1.—Principal chemical characteristics of First and Second Wall Creek waters of Salt Creek field.

on Fig. 1. With the exception of the extreme southern end of the field, the line limiting the oil area of the Second Wall Creek is also approxi-

mately the limit of clean oil. There has been very little encroachment of water in this sand within the last few years. Water encroachment in the First Wall Creek sand, however, has been very rapid and the area in which clean oil only is produced occupies but a small portion of the productive First Wall Creek area shown on the map.

Characteristics of Salt Creek Waters

The waters of the First, Second and Third Wall Creek sands, and the Lakota sand, are essentially solutions of sodium chloride and sodium bicarbonate, differing only in concentration and in the chloride-bicarbonate ratio. These determining characteristics may vary within the individual sand, depending on the position on the structure from which the sample is obtained. This is particularly true in water from the First Wall Creek sand. Correlations must be made, therefore, with known waters from wells in the immediate vicinity of the well having water trouble. The Shannon, Dakota, Sundance, and Tensleep waters contain sulfate in addition to chloride and bicarbonate. The Dakota is the first subsurface water that contains calcium and magnesium in appreciable amounts.

Twelve typical analyses of Salt Creek subsurface waters are given in Table 1. The composition of surface water is distinguished from subsurface waters, with exception of the Tensleep, by the predominance of calcium, magnesium and sulfate, and by low concentration. The surface water is sometimes used for drilling purposes.

The Shannon sand forms an escarpment around the field and does not enter seriously into underground production problems. Sodium sulfate is the chief soluble constituent in the majority of Shannon waters. Its variation is undoubtedly due to surface waters working through the outcrops. The Shannon is a comparatively dilute water, having a concentration of about 3000 parts per million. Since it has practically no scale-forming constituents, it has been used successfully as boiler water, but unfortunately the supply is inadequate for field requirements.

First Wall Creek Water

By far the greater number of analyses that have been made are of the First Wall Creek water. This is because the underlying Second Wall Creek is productive over a much larger area, and wells drilled to this sand and to the deeper sands always penetrate the First Wall Creek. The First Wall Creek is largely a solution of sodium chloride and sodium bicarbonate, as was noted above. Calcium, magnesium and sulfate appear only in negligible quantities and may be disregarded. This is particularly true of the sulfate, the presence of which is probably due to contamination with Shannon or with surface waters. The absence

TABLE 1.—*Typical Analyses of Salt Creek Subsurface Waters*

	(1) Shannon[a]	(2) 1st Wall Creek[b]	(3) 1st Wall Creek[c]	(4) 2nd Wall Creek[d]	(5) 2nd Wall Creek[e]	(6) 3rd Wall Creek[f]	(7) Dakota[g]	(8) Lakota Upper Bench[h]	(9) Lakota Lower Bench[k]	(10) Sundance Upper Bench[m]	(11) Sundance Lower Bench[n]	(12) Tensleep[p]
PARTS PER MILLION												
Sodium (Na)	1,139	2,668	3,641	3,864	6,388	6,506	3,691	1,558	1,048	4,580	4,006	651
Calcium (Ca)	6	6	Tr.	Tr.	29	18	30	Tr.	12	36	20	382
Magnesium (Mg)	0	4	0	0	33	8	12	0	Tr.	24	Tr.	62
Sulfate (SO_4)	1,944	0	Tr.	Tr.	0	60	82	Tr.	Tr.	334	850	1,126
Chloride (Cl)	20	390	2,500	4,300	5,801	8,500	5,150	1,550	800	6,361	4,580	956
Carbonate (CO_3)	18	115	241	Tr.	0	0	0	Tr.	Tr.	0	0	0
Bicarbonate (HCO_3)	500	6,130	4,871	2,850	7,216	2,650	975	1,465	1,440	1,046	1,725	127
Total solids (by evaporation)	3,420	6,210	10,500	10,700	15,801	17,500	10,340	4,420	2,910	12,381	10,316*	3,252
REACTING VALUES IN PARTS PER MILLION												
Sodium	49.52	115.99	158.37	168.01	277.74	282.89	160.47	67.73	45.57	199.71	174.16	28.33
Calcium	0.30	0.30			1.45	0.90	1.50		0.60	1.80	1.00	19.07
Magnesium		0.33			2.71	0.66	0.99			1.97		5.10
Sulfate	40.46					1.25	1.71			6.95	17.70	23.45
Chloride	0.56	11.00	70.52	121.30	163.63	239.77	145.27	43.72	22.57	179.38	129.19	26.97
Carbonate	0.60	3.84	8.03									
Bicarbonate	8.20	101.78	79.82	46.71	118.27	43.43	15.98	24.01	23.60	17.15	28.27	2.08
Total	99.64	233.24	316.74	336.02	563.80	568.90	325.92	135.46	92.34	406.96	350.32	105.00
REACTING VALUES IN PER CENT.												
Na	49.68	49.73	50.00	50.00	49.26	49.72	49.24	50.00	49.35	49.08	49.72	26.98
Ca	0.32	0.13	0.0	0.0	0.26	0.16	0.46	0.0	0.65	0.44	0.28	18.16
Mg	0.0	0.14	0.0	0.0	0.48	0.12	0.30	0.0	0.0	0.48	0.0	4.86
SO_4	40.60	0.0	0.0	0.0	0.0	0.22	0.52	0.0	0.0	1.70	5.05	22.33
Cl	0.56	4.73	22.30	36.10	29.02	42.14	44.58	32.30	24.40	44.10	36.90	25.68
CO_3	0.60	1.65	2.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HCO_3	8.24	43.62	25.20	13.90	20.98	7.64	4.90	17.70	25.60	4.20	8.05	1.99

* Ni, 53, H_2S, 185.

[a] Mosher-Dyke Well No. 1 (Loc. 36) NE. ¼ sec. 33, T. 40 N., R. 79 W.
[b] Midwest Ref. Co. Well No. 24A, SW. ¼ sec. 30, T. 40 N., R. 78 W.
[c] Midwest Ref. Co. Well No. 18, NW. ¼ sec. 25, T. 40 N., R. 79 W.
[d] Mammoth Oil Co. Well No. 409T-A, SE. ¼ sec. 20, T. 39 N., R. 78 W.
[e] Prairie O. & G. Co. Well No. 1, SE. ¼ sec. 2, T. 40 N., R. 79 W.
[f] Prairie O. & G. Co. Well No. 5, NE. ¼ sec. 20, T. 39 N., R. 78 W.
[g] Midwest Ref. Co. Well No. 19 L, NW. ¼ sec. 25, T. 40 N., R. 79 W.
[h] Midwest Ref. Co. Well No. 16 L, SW. ¼ sec. 23 T. 40 N., R. 79 W.
[k] Midwest Ref. Co. Well No. 16 L, SW. ¼ sec. 23 T. 40 N., R. 79 W.
[m] Midwest Ref. Co. Well No. 34 Sd, NW. ¼ sec. 35, T. 40 N., R. 79 W.
[n] Midwest Ref. Co. Well No. 12 Tp, SW. ¼ sec. 25, T. 40 N., R. 79 W.
[p] Midwest Ref. Co. Well No. 12 Tp, SW. ¼ sec. 25, T. 40 N., R 79 W.

of normal carbonate in most of the analyses would indicate that none exists in the water in its natural state, and that it is acquired through exposure of sample before analysis. The concentration as exemplified by total solids, and the relative proportion of chloride to bicarbonate are not uniform in the First Wall Creek water. The concentration around the edge of the field is about 2000 parts per million, and increases up-structure until a maximum of about 11,000 parts per million is reached within the productive limits. The increase is more pronounced on the eastern flank of the structure where the sands dip less steeply. The varying concentration of the First Wall Creek water was observed by Young and Estabrook,[1] who attributed it to a stagnant condition which was unaffected by water movements within the sand. The evaporating effect o expanding gas may also be a contributing factor in the high concentration of waters associated with the oil, as discussed by Mills and Wells.[2] It has been noted that the greatest concentration appears where encroaching edge water has channelled into the productive area. This variation in concentration is a condition that must be given careful consideration in the correlation and identification of the Wall Creek waters, and will be discussed later.

Second Wall Creek Water

The chemical constituents of Second Wall Creek water are similar to those of the First Wall Creek but differ in concentration and in the amounts of chloride and bicarbonate present. This is not always true, however, for there is water in or near the productive zone of the First Wall Creek sand that is identical with some Second Wall Creek water. The average concentration of typical Second Wall Creek watei is about 12,000 parts per million. For the purpose of comparison, the analyses given in Table 1 and the graph in Fig. 2 are the approximate extremes.

The concentration of Second Wall Creek water increases from south to north, as indicated by analyses 4 and 5 (Table 1 and Fig. 2), which are representative of the south and north ends of the field respectively. This increase in concentration is accompanied by a change in the chloride bicarbonate ratio. In the northwest, over an area of about 2 miles in extent, there is a decided decrease in the chloride-bicarbonate ratio, from 3:3 in the south end and 6:7 in the north to 1:7 in this area. It is to be noted that the chloride becomes lower while the bicarbonate becomes higher.

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[1] H. W. Young and E. L. Estabrook: Waters of the Salt Creek Field, Wyo. Petroleum Development and Technology in 1925, A. I. M. E., 199.

[2] R. Van A. Mills and R. C. Wells: The Evaporation and Concentration of Waters Associated with Petroleum and Natural Gas. U. S. Geol. Survey *Bull.* 693 (1919).

Third Wall Creek Water

Within the last year, water in four wells in the southern part of the field, which are producing from the Third Wall Creek sand, was found to have characteristics differing from the Second Wall Creek in that locality in concentration and in predominance of chloride. The average concentration of the water is about 17,000 parts per million, whereas the average Second Wall Creek concentration is about 12,000.

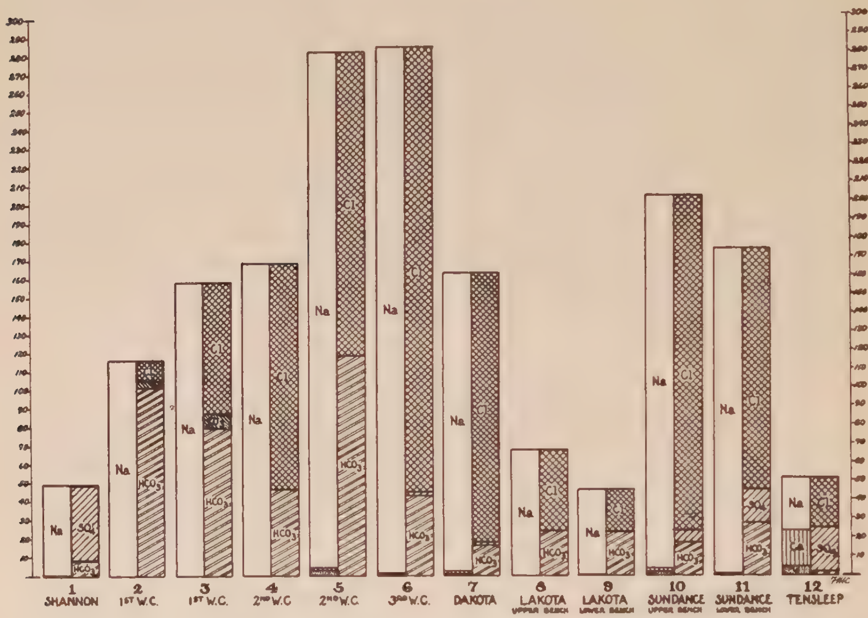

FIG. 2.—TYPICAL ANALYSES OF SALT CREEK WATERS. REACTING VALUES IN PARTS PER MILLION.

Dakota Water

Seven samples of Dakota water have been analyzed. The water is comparable to the Second Wall Creek in concentration but differs in the predominance of chloride and the persistence of sulfate. Calcium and magnesium are present in small amounts. The average concentration of this water is about 10,000 parts per million. Analysis No. 7 is representative.

Lakota Sand Water

The Lakota sand, occupying a position about 70 ft. below the Dakota, contains a water which is easily differentiated from the latter. It has a concentration of about 2200 to 4000 parts per million, and is free, or nearly free, from calcium, magnesium and sulfate.

An impervious stratum separates the sand into two benches in a portion of the Lakota area, and efforts are being made to differentiate the water in the two benches. Analyses 8 and 9 are of the waters found in these benches; comparison shows that the upper bench is higher in chloride and that the bicarbonate content remains unchanged.

Sundance Sand Benches

Sufficient drilling has been done to establish the presence of three distinct benches in the Sundance sand. The upper, or first bench, does not generally contain water or oil. The analysis of one sample of water found in this bench is shown in column 10 of Table 1. There are no satisfactory data to indicate the presence of water in the second bench. The third or lower bench contains water outside of the productive zone. Analysis No. 11 is fairly representative of this water. The Sundance is the first subsurface water below the Shannon to show the presence of sulfate to any great degree. While the analyses of two samples of water from the lower bench showed an exceptional amount of sulfate—1489 and 3905 parts per million, respectively—a third gave no indication of sulfate. In general, the water has a concentration of 9000 to 13,000 parts per million, with chloride predominating. The waters of the upper and lower benches are quite similar except that the water of the lower bench contains nickel and hydrogen sulfide.

Water from Tensleep Sand

The Tensleep sand has been penetrated by one well in Salt Creek, 12 Tp. SW. ¼ sec. 25, T. 40 N., R. 79 W. The high calcium and magnesium content is the distinguishing feature of this water. The sulfate is in excess of chloride and bicarbonate. It is a comparatively dilute water, having a concentration of about 3000 parts per million. This water, in spite of its scale-forming constituents, was used extensively in the field for drilling and domestic purposes. The well is 4400 ft. deep and the water, flowing to the surface, has a temperature of 174° F. It contains considerable hydrogen sulfide.

Water Condensed from Gas

One other water in the Salt Creek field enters into production probelms; that is, water condensed from natural gas. As the rising gas passes the point of saturation, due to decreasing temperatures, the water condenses on the casing and tubing, flows downward and accumulates in the bottom of the hole, whence it is pumped with the oil or bailed when the wells are cleaned. It is also frequently found in the tubing and in the tubing or gas anchors when they are pulled.

Water condensed from gas has no definite chemical characteristic other than a low concentration, varying from 200 to 2000 parts per

million. The average concentration of a large number of samples analyzed was 800 parts per million. The soluble salts are probably picked up by the condensate through contact with the sand at the bottom of the well.

The amount of water condensate in the wells varies from a trace—usually sufficient to cause line trouble in winter—to several barrels a day. In fact, some small pumping wells produce as much condensate as oil. Where considerable water of this kind is produced, the well usually pumps oil and water alternately, indicating the exhaustion of accumulations of water rather than a constant supply indicative of water encroachment.

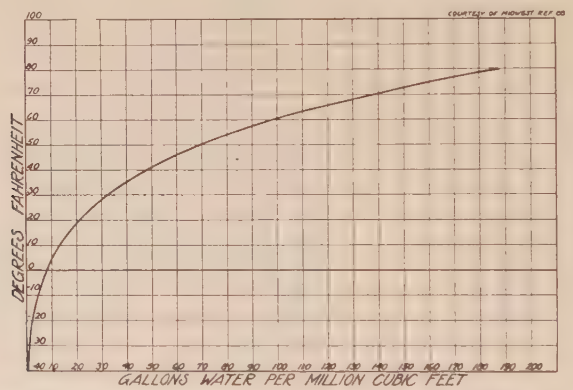

Fig. 3.—Maximum water content of natural gas at various temperatures.

The amount of water a well can "make" from this source is dependent on the temperature of the casinghead, the water content of the gas in the sand, and the quantity of gas produced. The temperature of the Second Wall Creek sand has been found to be about 100° F., and at a point 100 ft. below the surface approximately 53° F.[3] This variation in temperature between top and bottom of the hole causes considerable condensation, providing the water content is sufficient to saturate the gas at the lower temperature. The maximum water content of natural gas at various temperatures is shown by Fig. 3. Natural gas as it leaves the wells in Salt Creek is generally saturated with water vapor, and in summer it averages about 150 gal. of water per 1,000,000 cu. ft. of gas.

It has been observed that an increase in the gas production was accompanied by an increase in the amount of water condensate. Wells located low on the structure, particularly in the southeastern part of the field, are affected most. The order of appearance of condensate in wells was from the water line towards the apex of the structure, which seems to

[3] C. E. Van Orstrand: Private communication to the Midwest Refining Co.

be indicative that the water outside of the productive area is the source of the water in the gas.

Water-analysis Map

On account of the large number of analyses of Salt Creek waters available, and the necessity of correlating vertically through the stratigraphic column, it was necessary to arrange the data in a way to make them readily available. This was accomplished by plotting on a large-scale map the analyses at the respective well locations. The significance of the difference in concentrations and the ratios of the determining characteristics over the entire structure are thus shown.

H. W. Young, research engineer of the Midwest Refining Co., started this method of presenting water analyses and it was developed and elaborated by the authors. For the purpose of clarity, three water-analysis maps were compiled. On one were plotted 140 analyses, showing the characteristics of First Wall Creek water; on another the analyses of known Shannon, Second, and Third Wall Creek waters; on a third those of the Dakota, Lakota, Sundance and Tensleep. Each analysis shown on these maps is complete, with the chemical constituents expressed in parts per million.

The method used in plotting the analyses of waters is illustrated by Fig. 1. While the original maps have the complete analyses of all known waters, the scale of this map made it impossible to show more than the three distinguishing characteristics of the First and Second Wall Creek waters, with not more than two analyses in any quarter section. The First and Second Wall Creek waters were chosen for illustration because of the similarity of chemical content, which emphasizes the necessity of close discrimination in determining the source of water samples.

Correlation of Waters

The First Wall Creek, outside of its comparatively small productive area, carries water under a high hydrostatic head. This water is cased off in all wells drilled below the sand. If it is not excluded, it may have to be distinguished from other waters encountered in the well. Most of the problems of correlation have been in connection with the Second Wall Creek, which is the major producing sand of the field. It might seem difficult to distinguish between First and Second Wall Creek waters, on account of their apparent similarity, and that would be the case if the analyses were selected at random and not chosen with respect to the position of the source of the sample on the structure.

This is well illustrated in a recent example. A Second Wall Creek well, NW. ¼ sec. 19, T. 40 N., R. 78 W., began producing water with the oil. The analysis of this water, for instance, was found comparable with a sample representing First Wall Creek water in a well in SE. ¼ sec. 35,

T. 40 N., R. 79 W., which is 3 miles distant and near the apex of the structure where the concentration is abnormally high. From this comparison, the inference might be drawn that it was First Wall Creek water. However, in the vicinity of that well, the map shows several First Wall Creek analyses, from any one of which, but preferably the offset well in NW. ¼ sec. 19, the Second Wall Creek water is readily distinguishable. For the purpose of emphasizing the necessity of correlating the Wall Creek waters locally, the complete analyses of the three samples just mentioned are given in Table 2.

TABLE 2.—*Analyses Distinguishing Waters*

	First Wall Creek Well 16, SE. ¼ 35–40–79	Second Wall Creek Well 1, NE. ¼ 19–40–78	First Wall Creek Well 1, NW. ¼ 19–40–78
Na	5,321	4,504	1,785
Ca	Trace	Trace	10
Mg	0	0	11
SO_4	0	0	0
Cl	5,940	5,165	345
CO_3	132	Trace	54
HCO_3	3,610	3,060	4,128
TS	11,900	11,900	4,340

Referring to the graph (Fig. 2), it is obvious that comparison of First and Second Wall Creek analyses Nos. 3 and 5 is preferable to that of Nos. 3 and 4.

Operators in Salt Creek frequently request permission of the Government to abandon small producing Second Wall Creek wells in which water appears. Usually, if the well is in good mechanical condition and favorably located for any possible future gas or water drive, the Government recommends the suspension of operation of the well rather than its permanent abandonment. The course pursued depends on whether the water is First Wall Creek, Second Wall Creek or condensate. If, from the analysis, the water is found to be from the First Wall Creek, indicating infiltration due probably to defective casing or shut-off, abandonment of the well is recommended.

Edge Water Identified by Analysis

New wells drilled near the limits of the productive area may encounter water in the sand after their completion. If analysis identifies the water as edge water, abandonment operations may be hastened, thus eliminating the expenditure of time and money which would otherwise be required for the usual mechanical tests.

Of the many examples that might be cited to illustrate this type of assistance given to drilling operations in Salt Creek, the history of well

No. 3 NE. ¼ sec. 10, T. 39 N., R. 79 W., is chosen because the well gave valuable information regarding edge-water conditions in that particular part of the field.

In June, 1922, well No. 1 was drilled to the Second Wall Creek sand and produced considerable clean oil. Owing to mechanical difficulties it was necessary to abandon the well. In November, 1926, 4½ years later, well No. 3 was drilled 111 ft. distant from the old hole. During drilling a representative sample of First Wall Creek water was collected and its analysis filed for future reference.

Although the location of the well was near the estimated oil-water line, water was not anticipated because the previous well on approximately the same location had been a good producer. However, when the Second Wall Creek sand was penetrated to a depth of 68 ft., water rose to a height of 350 ft. The well was bailed for 5 hr. with no noticeable decrease in the water level. The proximity of the abandoned hole presented a possibility of infiltration from the First Wall Creek sand through a faulty abandonment. The water was promptly analyzed and identified as Second Wall Creek water. The well was immediately abandoned. The finding of Second Wall Creek water in this well not only showed that the well had no commercial value but also indicated an edge-water encroachment during the interval between the drilling of the two wells.

Chemical analysis was an important factor in mapping water encroachment in the Second Wall Creek sand. Owing to the possibility of the presence of water condensate, it was necessary to sample and analyze many showings of water in edge wells before the water could be definitely identified as edge water. Waters found in a number of wells near the edge of the productive area were found to be condensate and not encroaching edge water. Information of this kind is highly important, for without knowledge of the identity of the water, a water-oil contact line based simply upon the appearance of water, as determined by gage or centrifuge tests, might misrepresent the true condition and indicate edge-water encroachment, whereas none existed. In fact, this error occurred on one water map based solely upon centrifuge tests and tank gages.

It has been observed that dilution of edge water by condensate may occur at a well to such an extent that its identification is made more difficult. In such cases it is advisable to state the analysis in per cent. reacting values. It may then be possible to identify the water by the ratios of the reacting values, so that concentration may not enter into the interpretation of the analysis.

Analysis Applied to Drilling and Production Problems

The drilling of well No. 26A, SW. ¼ sec. 11, T. 39 N., R. 79 W., to the Second Wall Creek sand affords an interesting example of the application of the water analysis to drilling and production problems. The well

is located near a large fault. The sand in the downthrow side of the fault was known to contain water and in the upthrow to contain clean oil. When the sand was entered and the hole cleaned out, water accumulated at the rate of 1½ bailers per day. The question then arose, was the water native to the Second Wall Creek sand? If so, the well was in the downthrow side of the fault and the oil would not be sufficient to warrant further expenditure. A sample of the water was analyzed and found to be a First Wall Creek water. This showed that the sand itself was not water-bearing and that the well was in the upthrow side of the fault. The water in the sand was due either to First Wall creek water leaking in through a defective cement job or to water forced into the sand during drilling operation. If due to the latter cause it would be bailed or pumped out in a few days, leaving the sand at the well water-free.

The value of collecting samples of known waters as they are encountered in drilling is further emphasized in the recent development of the Lakota. One case of interest is that of well 19 L, NW. ¼ sec. 25, T. 40 N., R. 79 W. This well was drilled to the top of the Lakota sand and casing was landed. After standing idle for some time, a test showed the well to be making ½ bailer of water a day. The drill cuttings were unlike those of the Lakota sand. The question was raised whether the sand entered was Lakota or Dakota, and which of these sands was the source of the water. An analysis indicated that the water was from the Dakota. The casing was then cemented and the well deepened 8 ft. Water again appeared, which was identified by analysis as Lakota water. In this way it was established that the sand entered was the Lakota, and the water found in the well before cementing was Dakota water, which was not effectively excluded by the landed casing.

When underground waters are so similar in general chemical character as to make differentiation hazardous, the presence of some rarer element, even in minute quantity, may serve as a means of identification. The waters of the upper and lower benches of the Sundance sand afford an example of this. In all but one of the five known samples of water from the lower bench, nickel is found in amounts varying from 12 to 70 parts per million. This and the presence of hydrogen sulfide are the means by which the water of the lower bench is identified, since the water of the upper bench does not contain them.

Although iodine is found in certain waters in Salt Creek, the fact that it is not used for identification does not mean that its importance should be overlooked. The analyst should test for this as well as for other uncommon elements, as they may be a means for differentiating between waters.

In general, it may be stated that the identification and correlation of the waters below the Wall Creek sands have not been difficult because of the marked difference in their chemical characteristics

Natural underground waters very often are so contaminated by extraneous waters and cement that their original chemical characteristics are completely altered. Consequently it is difficult if not impossible to identify them.

Contamination caused by water used in drilling is common and is usually detected by the presence of calcium and sulfate in waters known not to contain them. The source of drilling water in Salt Creek is from surface ponds or Shannon and Tensleep sands, whose waters contain one or both of these radicals.

Cement contamination is indicated by the presence of the hydroxide radical OH. The bicarbonates, which are the important chemical constituents of the Wall Creek waters, react with the oxides in the cement to form hydroxides. While the identity of these waters is thus destroyed the presence of OH very often is an indication of a poor cement job. First Wall Creek water having slow ingress to and around the shoe of a newly cemented water string will invariably contain hydroxide, indicating that the cement has set improperly and the shut-off was not effective.

The intermingling of waters from different sands is a source of contamination and very often is sufficient to obscure their identity. Problems of this nature may require mechanical work to isolate the waters before reliable chemical information can be obtained.

Frequently water which has "backed" into the formations during drilling will reappear after casing has been successfully cemented or after the well has been put to pumping, and without chemical analysis might be confused with upper, "stray" sand or edge water. Well 29 AX, SW. ¼ sec. 32, T. 40 N., R. 78 W, is a typical example. First Wall Creek water had access to the Second Wall Creek sand during the abandonment of well 29 A. After 29 AX was drilled and put to pumping considerable First Wall Creek water was produced with the oil, but was eventually exhausted. It is interesting to note in connection with this that well 30 A, on the same property, produced considerable condensate, which gas presumably had picked up from the "watered" sand in the vicinity of well 29 A.

Occasionally, as an experiment, a lease man will put into a well some foreign substance, such as sodium chloride or calcium chloride, in an endeavor to prevent freezing of water in lead lines. This type of contamination is easily identified because of the unusual chemical nature of the water, but at first it is likely to be perplexing to the analyst.

Sampling Water for Analysis

Too little attention has been given to the matter of sampling of water for chemical analysis. Frequently this duty is left to the drilling crew or pumper, with the result that the sample is not satisfactory. It should be done by a chemist or an engineer, or someone who appreciates the impor-

tance of obtaining a sample that is representative and free from contamination. The container should be washed out with the water to be sampled and should be sealed immediately after filling to prevent changes due to exposure. The container should be labeled and if it is to be shipped it should be packed carefully to prevent breakage.

Information regarding the source of the sample and the condition of the well from which the sample was obtained are equally important. This information is important as an aid in identifying the water, and is of inestimable value for future reference. The value of the information concerning the source of the sample is impressed upon one who has had occasion to review the records and files of water analyses. The mere statement of a chemical analysis means nothing to an engineer unless it is accompanied by the facts of the case, which must be considered in the interpretation of the analysis. Depths of sand and points where waters are encountered, amounts of water, casing points, and dates are essential facts. Very often waters submitted for analysis are not representative, and therefore are the source of error and confusion in later correlation. When adequate information is furnished and filed with the analysis, it affords a check on the latter. The office of the Geological Survey in Salt Creek has prepared a form that is filled out for every sample of water submitted for analysis.

Acknowledgments

The writers are indebted to the Midwest Refining Co. for many of the analyses used in this paper, and express their thanks to its research engineer, H. W. Young, for his cooperation with the personnel of the Midwest, Wyoming, Station of the U. S. Geological Survey. It was through the generous exchange of analyses and water data that a more comprehensive understanding of Salt Creek waters was made possible. Mr. Young reviewed this paper and offered many helpful suggestions.

To Herman Stabler, chief of the Conservation Branch, U. S. Geological Survey, the writers express their appreciation for his review of the paper and constructive criticisms.

F. M. Cole, assistant engineer, U. S. Geological Survey, drafted the illustrations.

Core Studies of the Bradford Sand from the Bradford Field, Pennsylvania*

By Charles R. Fettke,† Pittsburgh, Pa.

(New York Meeting, February, 1929)

The Bradford field of northwestern Pennsylvania and adjacent portions of New York state has attracted world-wide attention in recent years on account of the remarkable success that has been attained in the application of water-flooding as a means of increasing the extraction of oil from a pool that had almost reached the economic limit by ordinary production methods. It is one of the few large oil fields in which artificially conducted water drives have thus far proved successful, although many attempts have been made to apply them elsewhere. As detailed a knowledge as possible of the character of the producing sand in this field is therefore of considerable interest, not only from a scientific but also from a practical standpoint. Outside the Bradford field, such knowledge should aid operators in determining whether or not their sands are amenable to flooding. In the Bradford field itself flooding operations are not uniformly successful over the approximately 85,000 acres of productive area, due in many instances primarily to variations in sand conditions. A knowledge of just what these variations are would often be a great aid in overcoming the difficulties, or else would save considerable sums of money which might otherwise be wasted in experimenting in areas where the chances of success are very small.

Realizing that more precise information in regard to the nature of the reservoir rock was essential to improvements in the methods of oil recovery, the Northwestern Pennsylvania Oil Producers Assn., by private subscription of its members, took a core of the Bradford sand from a well ½ mile west of Custer City, Pa., during the spring of 1925. The Forest Oil Co. also took a core of the same sand from a well about 8 miles east of Bradford at that time. The cores were submitted to the United States Geological Survey for study and A. F. Melcher[1] has published the results of porosity determinations on the Custer City core.

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* Published by permission of the State Geologist of Pennsylvania.

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[1] A. F. Melcher: The Porosity of the Bradford Oil Sand near Custer City, Pa., and Its Relation to the Production of Oil. U. S. Geol. Survey, Memorandum for the Press No. 1008 (1925).

On account of the expense involved in taking cores with a diamond drill, no further coring was undertaken in the Bradford field until the spring of 1928, when core-drilling with cable tools was introduced by the Sloan and Zook Co., which had previously employed this method of taking cores successfully in the near-by Kane field. During the summer of 1928, three cable-tool core barrels were kept in almost continuous operation. Through the courtesy of the various operators concerned, the cores have been made available to the writer for examination in connection with a geological survey of the Bradford oil field for the Pennsylvania Geological Survey. A rather detailed study of two of these has thus far been made, the results of which are incorporated in this paper.

Method of Coring and Cost

Two types of cable-tool core barrels have thus far been employed in the Bradford field—the Baker and the Keystone. In principle of operation they are essentially the same. Both consist of two main parts, an outer drilling barrel and an inner core-retaining tube. The drilling barrel is composed of three parts; a drill-barrel head, a drill barrel, and a drill-barrel shoe. In the case of the Baker barrel, the drill-barrel head is equipped with a back-pressure valve which opens downward. This serves to force a stream of water down between the drill barrel and the core tube as the bit descends, which washes away cuttings from around the drill-barrel shoe. The Keystone barrel does not have such a valve. The Baker drill-barrel shoe has eight cutting teeth which are faced with a special alloy steel. At Bradford, stellite is being used for this purpose. The Keystone bit has only two cutting edges. These, as well as the periphery of the shoe, are faced with stellite. The cutting edges of the Keystone shoe are similar to the cutting edge of the regular standard cable-tool bit with the central part removed to allow the shoe to slip over the core tube. In both types a core-tube trimmer shoe with sharp bevel edge faced with stellite is screwed on to the core tube. The Baker trimmer shoe has a loose split trap ring mounted on the inside to retain the core. The Keystone trimmer shoe does not have such a ring; it has a slightly smaller inside diameter than the rest of the core tube, which aids in retaining the core. No trouble has been experienced with portions of the core dropping out, as this is usually wedged so tightly in the core tube that considerable pressure has to be exerted to remove it. The Baker core-tube head has a ball check valve to permit the discharge of drilling water trapped in the core tube as it fills with core. The Keystone core-tube head is open. The core-tube heads have a shoulder, which catches, when the drilling barrel is raised, on the shoulder formed by the drill-barrel shoe, which has a smaller inside diameter than that of the drill barrel itself.

Before coring is started, the hole should be bailed as clean as possible so that the core tube will not be filled with mud and cavings before reaching the bottom. This must be repeated each time the tools are removed. Careful steel-line measurements should also be taken each time just prior to running the tools into the hole, so that the recovery of core can be checked with the actual distance penetrated. Coring, of course, should be started before the sand itself has been penetrated by the drill. In some parts of the field, by-passing is known to occur in the upper part of the sand and it is, therefore, important to have this part available for examination.

Experienced cable-tool drillers in the Bradford field have had no difficulty in learning to operate the core barrel. The core barrel replaces the standard bit at the end of the drill stem. A full-size hole is drilled, but where a considerable thickness of sand is cored it is frequently necessary to ream before reaching bottom. At least 20 ft. of water should be in the hole. The motion is the same as for regular drilling, but slower. As drilling proceeds the drill barrel drops down over the core tube, which is stationary during the drilling operation, except when the drill-barrel shoe has drilled about 3/4 in. below the core-tube trimmer shoe, at which time the drill barrel strikes the knocking head, which drives the core tube over the core. In the case of the Baker barrel, the hydraulic pressure built up at the end of the stroke also aids in causing the core tube to follow down over the core. Care must be taken not to remove the core tube from the bottom of the hole after coring has started.

At Bradford, the practice is to take from 4 to 7 ft. of core at a time. In most instances, the best results are obtained by not exceeding 5 ft. The cores are not in one piece, like diamond-drill cores, but are in biscuit form, because of wobbling of the barrel in the hole. In cores from the Bradford sand, these biscuits range from 1/2 to 2 in. thick.

Usually it is necessary, after one or two runs, to dress the drill-barrel shoes. They have to be taken to a machine shop to be built up and refaced with stellite and then ground to gage on an emery wheel. At least two extra shoes are kept on hand so that the drilling operation will not be held up while shoes are being dressed.

The writer is indebted to the Sloan and Zook Co. for the data of Table 1, on the coring of Summit G-4 well. A Keystone core barrel was used. Both day and night tours were run. Neither driller had had any previous experience in the use of the core barrel.

Running daylight tour only, 2 1/2 days were required to take a 33-ft. core from the Bovaird Oil Co. Schofield 96 well. This includes the time required to rig up but does not include 1/2 day spent in changing from a manila rope to a wire line. A Baker core barrel was used. Reaming was not necessary. The driller had had no previous experience in its operation. The drilling contractor was paid $30 per day for the use

of the rig, besides footage. The cost of dressing bits was approximately $42.

TABLE 1.—*Data on Coring of Summit G-4 Well*

Time coring started	12:40 p.m. Friday, Aug. 24, 1928
Time coring was completed, including reaming	6:00 a.m. Tuesday, Aug. 28, 1928
Total time for coring	89 hr., 20 min.
Deduct: Shut down for belt repairs, 2 hr., 45 min.	
6:00 p.m. Saturday to 12:00 a.m. Monday, 30 hr.	
Actual time of coring, including reaming	56 hr., 35 min.
Total number of feet cored	73 ft., 1 in.
Percentage of core obtained	98.9
Average speed	1 ft. in 45 min.
Maximum speed	1 ft. in 30 min.
Time spent in reaming	10 hr., 45 min.
Time required to change bit (remove old one and install new one)	1 hr., 15 min.
Average time tools were out of hole between runs	37 min.

Cost

Paid drilling contractor, beside footage	$180.00
Cost of keeping the record	37.00
Dressing three bits (does not include cost of stellite)	20.00
39 tin containers for core	39.00
Tape for sealing containers	0.40
Services of two men and tractor for 4 hr	8.00
Depreciation of equipment	65.00
Total	$349.40
Cost per foot	4.78
Cost per foot, deducting for extra drilling cost due to shutdown over Sunday	4.37

STRATIGRAPHIC POSITION OF THE BRADFORD SAND

That the Bradford sand was deposited under marine conditions is indicated by the fact that marine fossils are very sparingly distributed throughout the main body of sand. Fossils from it were submitted to Charles Butts, of the United States Geological Survey, who found that they represented forms of which appearance in the section affords the basis for separating the Chemung from the underlying Portage beds.[2] The sand apparently lies at or near the base of the Chemung formation and therefore is of upper Devonian age. Just above the sand itself, sometimes separated from it by a few inches of shale, usually there is one thin bed, sometimes more, of fine-grained gray calcareous sandstone, which contain an abundance of marine shells.

[2] J. B. Newby, P. D. Torrey, C. R. Fettke and L. S. Panyity: The Geology of the Bradford Oil Field. Amer. Assn. Petr. Geol. (1927).

Location of Cores Studied

The two cores of the Bradford sand thus far studied in detail were taken from Summit G-4 well of the Sloan and Zook Co. and Schofield 96 well of the Bovaird Oil Co. The former is about $3\frac{1}{2}$ miles north of Rew in the central part of the Bradford field and the latter $1\frac{1}{2}$ miles southeast in the southeastern part of the field. Rew is 7 miles southeast of Bradford. The writer was present during much of the time that the sand was being cored in Summit G-4 well and in the upper part in Schofield 96.

Characteristics of the Bradford Sand

The Bradford sand, while exhibiting a remarkable continuity and a considerable degree of homogeneity over approximately 85,000 acres of proved territory, is by no means uniform over the entire area of the field. Wide variations in total thickness and number and thickness of shale breaks frequently occur between adjacent properties and even adjacent wells. Cross-bedding, however, appears to be absent. At any rate it is a negligible factor. Core studies have brought out variations in porosity, uniformity and actual size of grains, and character and amount of cementing material, both vertically and laterally, in the sand. In general, however, it can be stated that these variations are not nearly as great as in some of the other oil sands of Pennsylvania, as, for example, those of the Venango group that have been studied in detail by the writer.[3]

Detailed sections of the Bradford sand as developed in Summit G-4 and Schofield 96 wells are shown graphically by the usual conventional symbols in Fig. 3; the latter is also shown in Table 2.

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[3] C. R. Fettke: Core Studies of the Second Sand of the Venango Group, from Oil City, Pa. Petroleum Development and Technology in 1926, A. I. M. E., 219.

Ten Years' Application of Compressed Air at Hamilton Corners, Pa., with Core Studies of the Producing Sand. Petroleum Development and Technology in 1927, A. I. M. E., 330.

TABLE 2.—*Section of Core from Schofield 96 Well*

Thickness, Feet	Character of Ground	Depth in Feet	
		Top	Bottom
0.67	Shale		
0.81	Fine-grained hard calcareous gray sandstone. Very fossiliferous		
	Top of Bradford Sand		
1.00	Fine-grained moderately hard chocolate brown sandstone	1675.48	1676.48
2.21	Fine-grained moderately friable dark chocolate brown sandstone	1676.48	1678.69
0.46	Fine-grained moderately hard chocolate brown sandstone	1678.69	1679.15
3.23	Fine-grained friable chocolate brown sandstone	1679.15	1682.38
1.12	Fine-grained moderately hard chocolate brown sandstone	1682.38	1683.50
2.21	Fine-grained moderately friable dark chocolate brown sandstone	1683.50	1685.71
0.62	Fine-grained moderately hard dark chocolate brown sandstone	1685.71	1686.33
0.63	Fine-grained moderately friable dark chocolate brown sandstone	1686.33	1686.96
0.37	Fine-grained moderately hard dark chocolate brown sandstone	1686.96	1687.33
0.98	Fine-grained moderately friable dark chocolate brown sandstone	1687.33	1688.31
0.27	Fine-grained moderately hard dark chocolate brown sandstone	1688.31	1688.58
0.30	Fine-grained moderately friable dark chocolate brown sandstone	1688.58	1688.88
0.62	Fine-grained moderately hard dark chocolate brown sandstone	1688.88	1689.50
1.00	Fine-grained moderately friable dark chocolate brown sandstone	1689.50	1690.50
1.00	Fine-grained hard chocolate brown sandstone	1690.50	1691.50
1.06	Fine-grained moderately friable chocolate brown sandstone	1691.50	1692.56
0.63	Fine-grained hard chocolate brown sandstone	1692.56	1693.19
2.00	Fine-grained moderately friable chocolate brown sandstone	1693.19	1695.19
1.31	Fine-grained hard chocolate brown sandstone	1695.19	1696.50
0.96	Fine-grained moderately friable dark chocolate brown sandstone	1696.50	1698.46
0.12	Fine-grained hard dark chocolate brown sandstone	1698.46	1698.58
1.09	Fine-grained moderately friable dark chocolate brown sandstone	1698.58	1699.67
0.73	Fine-grained hard dark chocolate brown sandstone	1699.67	1700.40
0.66	Shale	1700.40	1701.06
0.11	Fine-grained hard dark chocolate brown sandstone	1701.06	1701.17
0.33	Shale	1701.17	1701.50

TABLE 2.—(*Continued*)

Thickness, Feet	Character of Ground	Depth in Feet	
		Top	Bottom
0.46	Fine-grained very hard dark brownish-gray sandstone	1701.50	1701.96
0.33	Shale	1701.96	1702.29
0.42	Fine-grained very hard dark brownish-gray sandstone	1702.29	1702.71
0.17	Shale	1702.71	1702.88
0.16	Fine-grained very hard dark brownish-gray sandstone	1702.88	1703.04
0.25	Shale	1703.04	1703.29
0.75	Fine-grained very hard dark brownish-gray sandstone	1703.29	1704.04
0.09	Shale	1704.04	1704.13
0.41	Fine-grained very hard dark brownish-gray sandstone	1704.13	1704.54
0.42	Shale	1704.54	1704.96
0.75	Fine-grained very hard dark brownish-gray sandstone	1704.96	1705.71
0.50	Shale	1705.71	1706.21
0.12	Fine-grained very hard dark brownish-gray sandstone	1706.21	1706.33
	Shale		

MINERALOGICAL COMPOSITION

In thin section, under the microscope, typical Bradford sandstone is made up principally of an interlocking mosaic of fine quartz grains, the

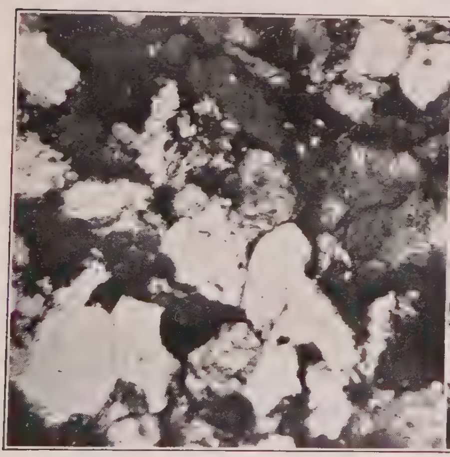


FIG. 1.—SANDSTONE OCCURRING AT A DEPTH OF 1741.92 FT. IN SUMMIT G-4 CORE. SECTION CUT PARALLEL TO BEDDING. TAKEN WITH CROSSED NICOLS.

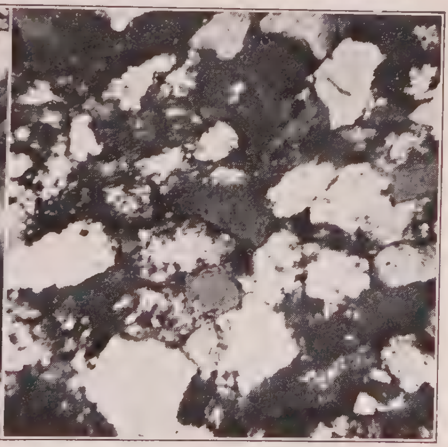


FIG. 2.—SECTION OF SAME SANDSTONE CUT PERPENDICULAR TO BEDDING. TAKEN WITH CROSSED NICOLS.

(½ in. = ⅛ mm.)

majority of which are pronouncedly angular. Figs. 1 and 2 are photomicrographs of the sandstone occurring at a depth of 1741.92 ft. in the Summit G-4 core, taken with crossed nicols. Fig. 1 represents a section cut parallel to the bedding and Fig. 2 perpendicular to it. In addition to

the quartz grains, a few flakes of muscovite and biotite mica are present and an occasional plagioclase grain. Some of the mica flakes have been bent around the quartz grains. A small amount of interstitial material, consisting of an aggregate of brown micalike and other clay material, occurs between the quartz grains, but it is not uniformly distributed. Silica, as a secondary crystalline outgrowth from the original quartz grains, and the small amounts of clay material mentioned form the bond. Only one or two calcite grains were observed. Occasional clusters of minute pyrite crystals, clearly of secondary origin, are present. A separation with bromoform yielded only 0.34 per cent. of heavy mineral grains, about 70 per cent. of which are pyrite; 15 per cent. of a colorless mineral, probably a pyroxene; 10 per cent. of zircon; and 5 per cent. of tourmaline. Only a few calcite grains occur in the concentrate. Many of the zircon grains show crystal outlines, although usually these are at least partly rounded. The tourmaline occurs as partly rounded prismatic grains. In the section, perpendicular to the bedding, stratification is faintly indicated by the alignment of the occasional mica flakes and some of the elongated quartz grains parallel to the bedding plane.

The sandstone from which these sections were prepared has a porosity of 15.7 per cent. Only 1.42 ft. above the point where this sample was taken—at 1740.5 ft., in the same stratum—the porosity was only 8.9 per cent. Examination of a thin section from this horizon revealed the presence of large amounts of calcite, which have been rather uniformly deposited between the quartz grains; 0.42 ft. above this the porosity is 14.4 per cent. The deposition of calcite is confined to a thin seam in what otherwise appears to be a uniform stratum.

A thin section from the sandstone with a porosity of 10.1 per cent., occurring at a depth of 1761.88 ft. near the top of a stratum 2.33 ft. thick, was found to contain more muscovite and biotite than the other sections examined and considerably more of the interstitial brown clay material. Calcite is sparingly present at this horizon. Another section, from a thin seam with a porosity of only 6.5 per cent. at a depth of 1766.5 ft., shows considerably more silica deposited as a secondary crystalline outgrowth from the original quartz grains than the other sections. Some cryptocrystalline silica, probably also of secondary origin, is present. The clay content is small.

Chemical Composition

A chemical analysis of the sandstone occurring at the depth of 1741.92 ft. in the Summit G-4 well was made according to the methods recommended by Washington.[4] The sample was first crushed to pass through a 100-mesh sieve, then extracted with carbon tetrachloride followed by petroleum ether, and dried at 130° C. The results are shown in Table 3.

[4] H. S. Washington: Chemical Analysis of Rocks, 2d Ed. 1910.

TABLE 3.—*Chemical Analysis of Bradford Sandstone*
From a Depth of 1741.92 Ft. in Summit G-4 Well

	Per Cent.
SiO_2	86.89
Al_2O_3	6.95
Fe_2O_3 (includes FeO)	2.55
MgO	0.42
CaO	0.07
Alkalies	not determined
H_2O (combined)	0.89
CO_2	trace
C (organic)	0.30
	98.07

Organic carbon was determined in a combustion furnace. The presence of 0.3 per cent. organic carbon indicates that not all the petroleum residues were removed by the extraction with carbon tetrachloride and petroleum ether. The sample analyzed was carefully examined for carbonized plant remains, such as sometimes occur in the Bradford sand, before it was crushed. None were observed.

Porosity

Table 4 shows the porosities of the sandstone from the cores obtained from Schofield 96 well. These porosities and those of the Summit G-4 are also shown graphically by porosity profiles opposite the columnar sections of the cores in Fig. 3. The determinations were made according to the method described by Melcher.[5] Extraction of the crushed sandstone with carbon tetrachloride and petroleum ether, preliminary to the determination of the volume of the individual grains, was not satisfactory, as it was practically impossible to completely remove the air from the disintegrated sand in the pycnometer after such treatment, and the densities obtained for the grains were invariably low. The crushed sandstone was heated, therefore, in a silica crucible over a Bunsen burner for 20 min., with free access of air to completely remove the petroleum residues that apparently caused the air to adhere to the grains so tenaciously. After this treatment, no further difficulty was experienced.

The Bradford sand as developed in Summit G-4 well can be conveniently divided into three parts; namely, a top pay, a shale break, and a bottom pay. The top pay extending from 1735 to 1764.04 ft., contains 25.58 ft. of sandstone with an average porosity of 14.4 per cent. The

[5] A. F. Melcher: Determination of Pore Space of Oil and Gas Sands. *Trans.* A. I. M. E. (1921) **65**, 469.

Texture of Oil Sands with Relation to the Production of Oil. *Bull.* Am. Assn. of Petr. Geol. (1924) **8**, 731.

TABLE 4.—*Total Pore Space by Volume in Schofield 96 Core*

Depth in Feet	Pore Space by Volume, Per Cent.	Density of Grains	Loss by Extraction with Carbon Tetrachloride and Drying at 130° C.,[a] Per Cent. by Weight	Loss by Ignition[a] Per Cent. by Weight
1675.98	14.6	2.6579	1.2	2.4
1676.48	17.9	2.6616	1.6	2.8
1676.81	21.8	2.6623	2.1	3.6
1677.98	22.7	2.6673	2.2	3.8
1678.50	22.3	2.6857	2.5	4.2
1678.92	20.8	2.6648	2.2	3.6
1679.75	21.8	2.6650	2.2	3.6
1682.96	16.8	2.6730	1.9	3.3
1684.00	19.5	2.6689	1.9	2.9
1684.58	19.3	2.6681	2.2	3.4
1685.38	19.3	2.6681	2.2	3.4
1686.08	17.9	2.6674	2.1	3.3
1686.63	16.3	2.6710	1.9	3.5
1687.17	13.5	2.6916	1.3	2.9
1687.83	15.9	2.6774	2.0	3.5
1688.46	16.4	2.6793	1.8	3.4
1688.79	16.6	2.6801	1.8	3.3
1689.17	14.0	2.6830	1.2	3.1
1690.00	21.6	2.6660	2.0	3.5
1691.00	9.9	2.6522	0.9	1.8
1692.00	17.7	2.6637	1.6	3.0
1692.88	14.5	2.6645	1.4	2.4
1694.19	14.7	2.6709	1.4	2.5
1696.00	14.8	2.6653	0.9	1.7
1697.50	14.9	2.6805	1.1	2.4
1698.52	14.5	2.6807	1.1	2.3
1699.13	15.1	2.6975	1.2	2.7
1700.00	10.8	2.7049	1.5	3.0
1701.10	10.4	2.6709	1.0	2.3
1705.33	10.5	2.6611	0.7	1.8

[a] The samples of sandstone on which the porosity determinations were made were wrapped in paper at the well. Several months elapsed before they were crushed, so that most of the moisture and oil had evaporated. The loss by ignition includes the loss by extraction, as a fresh sample was used in each case.

shale break extends from 1764.04 to 1783.25 ft. and contains only 2.67 ft. of sandstone, with an average porosity of 9.0 per cent. The bottom pay extends from 1783.25 to 1799.58 ft. and contains 11.17 ft. of sandstone with an average porosity of 13.7 per cent. There is sufficient volume represented by the pore space of the upper pay so that, if it were 100 per cent. saturated, it would contain 27,667 bbl. of oil per acre while the lower pay would contain 11,971 bbl., making a total of 39,638 barrels.

The pay sand in the Schofield 96 well extends from 1675.48 to 1700.40 ft. without a single shale parting. This 24.92 ft. of sandstone has an average porosity of 17.2 per cent. A sand body of this thickness and porosity would contain 33,314 bbl. of oil per acre if it were 100 per cent. saturated. The lower bench of the Bradford sand in this well,

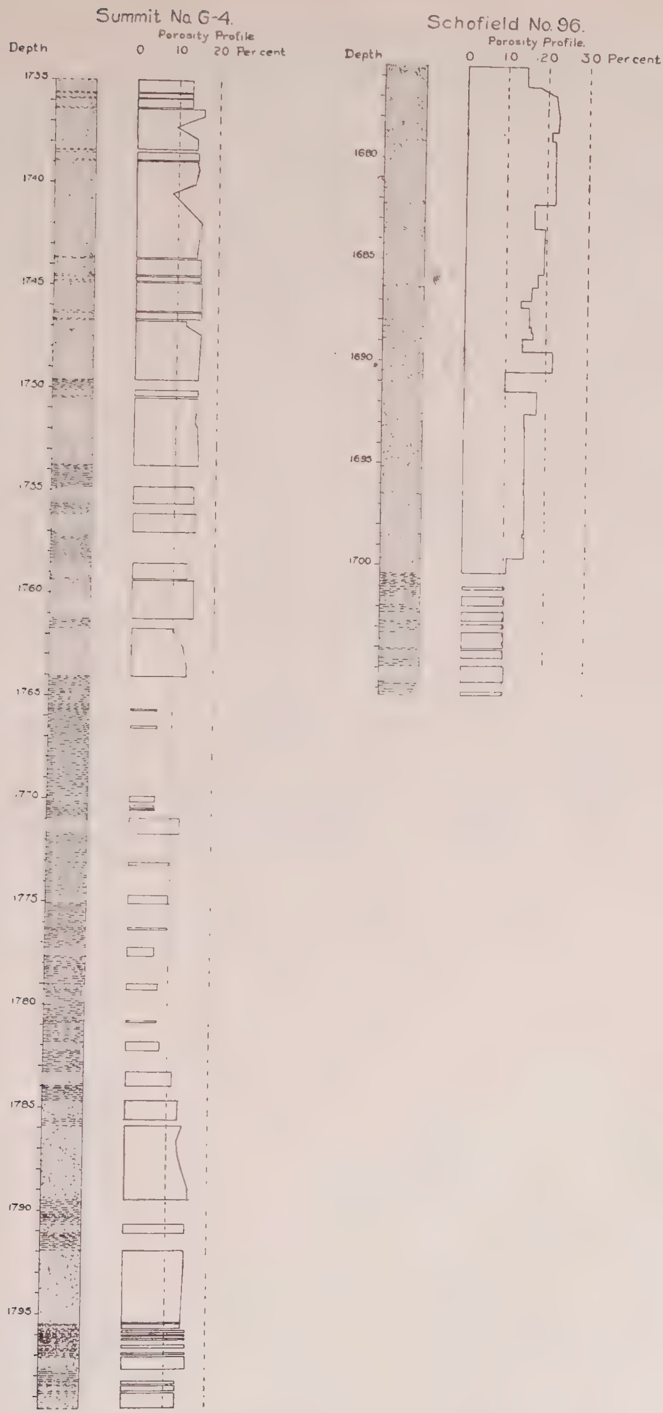
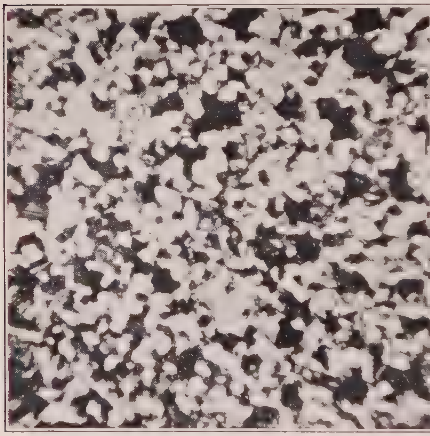


FIG. 3.—SECTIONS AND POROSITY PROFILES OF CORES FROM SUMMIT G-4 AND SCHOFIELD 96 WELLS.

extending from 1700.40 to 1706.33 ft., contains only 3.19 ft. of sandstone with an average porosity of 10.5 per cent.

Some idea of the nature of the pores in the Bradford sand can be obtained from the photomicrographs shown in Figs. 4 and 5, polished surfaces by reflected light. The specimens were first hardened with bakelite varnish to prevent the tearing out of any of the grains and then polished in the usual manner. The light areas show the mineral grains while the black ones represent the pores. Fig. 4 represents a surface parallel to the bedding and Fig. 5, one perpendicular to it, of a sample taken at a depth of 1741.92 ft. in the Summit G-4 well. The bedding is clearly shown in the latter by the alignment of the grains. The sample has a porosity of 15.7 per cent.



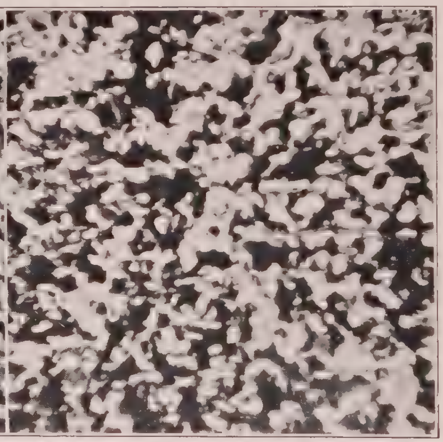


FIG. 4.—POLISHED SURFACE OF SANDSTONE PARALLEL TO THE BEDDING OCCURRING AT A DEPTH OF 1741.92 FT. IN SUMMIT G-4 CORE.

FIG. 5.—POLISHED SURFACE OF THE SAME SANDSTONE PERPENDICULAR TO THE BEDDING.

($\frac{1}{2}$ in. = $\frac{1}{2}$ mm.)

Size and Shape of Grains

Five representative samples were selected from different parts of the Summit G-4 core and four from the Schofield 96 and crushed to individual grain size. A set of Tyler standard screen sieves was used for the mechanical analysis. Table 5, giving the position in the cores as well as the porosity of the samples, shows the range in grain size and the small amount of variation between different horizons. These are also shown graphically by means of cumulative percentage curves in Fig. 6.

A comparison of porosity with grain size of the nine samples of Bradford sand analyzed indicates that the percentage of fine material—that is, grains that pass through a 325-mesh sieve—is one of the important factors in determining the porosity of the sand. The lower this percentage,

the higher the porosity, since the fine particles fill the voids between the larger ones and thus reduce porosity. With the exception of the sample

TABLE 5.—*Screen Analyses of Nine Samples of Bradford Sand*
From Summit G-4 and Schofield 96 Cores

Size of Opening, Millimeters		Summit G-4					Schofield 96			
Through	Caught	Depth 1737.92, Porosity 14.8, Per Cent.	Depth 1741.92, Porosity 15.7, Per Cent.	Depth 1751.88, Porosity 15.5, Per Cent.	Depth 1770.04, Porosity 6.0, Per Cent.	Depth 1788.92, Porosity 15.3, Per Cent.	Depth 1677.98, Porosity 22.7, Per Cent.	Depth 1679.75, Porosity 21.8, Per Cent.	Depth 1690.00, Porosity 21.6, Per Cent.	Depth 1699.13, Porosity 15.1, Per Cent.
0.295	0.208	0.0	0.6	0.0	0.0	0.0	1.3	0.0	0.0	0.0
0.208	0.147	4.4	2.9	3.3	4.0	8.7	29.9	15.9	13.9	2.7
0.147	0.104	27.4	25.3	31.1	24.6	33.9	39.9	45.2	53.1	32.5
0.104	0.074	29.4	33.4	31.0	22.3	26.1	16.6	20.3	17.0	31.9
0.074	0.061	16.1	16.1	16.6	14.9	11.2	4.4	5.9	4.4	13.7
0.061	0.046	5.6	5.6	5.9	7.6	5.2	1.9	2.4	2.9	4.6
0.046	0.044	4.2	4.3	2.6	6.0	4.1	1.9	2.2	2.4	4.8
0.044		12.8	12.7	9.5	20.5	10.9	3.9	8.1	6.5	9.7

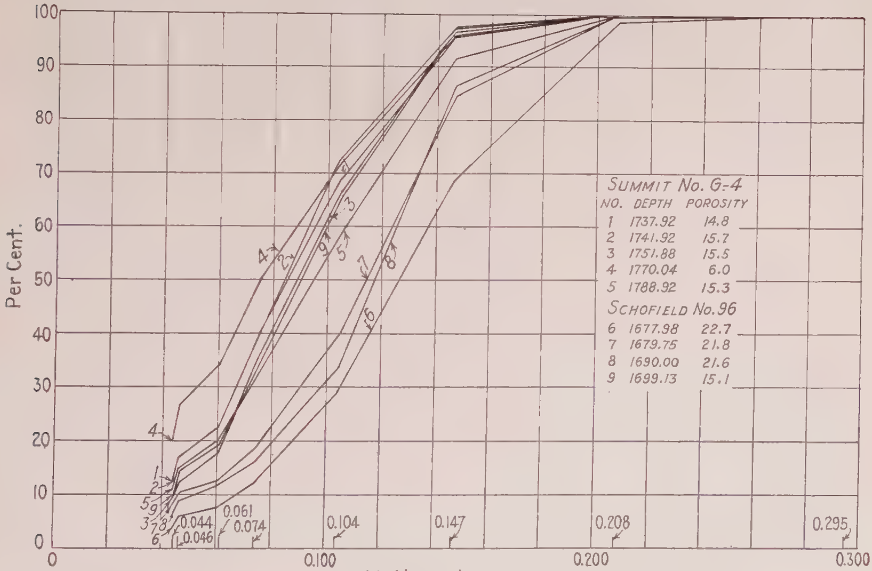


FIG. 6.—CUMULATIVE PERCENTAGE DISTRIBUTION OF DIAMETER OF GRAINS OF NINE SAMPLES OF BRADFORD SAND.

from a depth of 1770.04 ft., which represents a thin seam of sandstone in the shale break, the five samples from Summit G-4 core show a very close similarity in grain size. In the Schofield 96 core, the more porous

upper portion of the sand is made up of somewhat coarser grains than the lower part.

The uniformity of grain size and the fine character of typical Bradford sand are shown in Fig. 7 representing a photomicrograph of the material obtained by crushing a sample of the sandstone, occurring at a depth of 1741.92 ft. in the Summit G-4 well, to individual grain size. About 78 per cent. of the grains are angular, 12 per cent. subangular, 7 per cent. fairly well rounded, and 3 per cent. rounded.

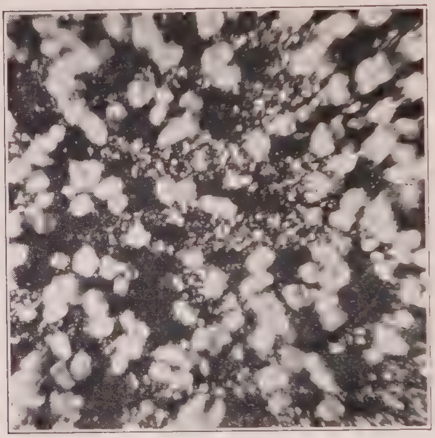


Fig. 7.—Grains from sandstone occurring at a depth of 1741.92 ft. in the Summit G-4 core.
(½ in. = ½ mm.)

Oil Content of Sand

Seven samples from 4 to 8 in. long were taken from the core of Summit G-4 well and one from the Schofield 96 for the determination of their oil content. They were wrapped in tinfoil as soon as they were removed from the core barrel and placed in tin containers, which were sealed. The method of procedure for determining the oil and water content was similar to that described in a previous paper.[6] The results are shown in Table 5.

The average oil content of the four samples from the upper pay of the Summit G-4 well was 46.5 per cent. of their total pore space, while that of the three from the lower pay was 40 per cent. The single sample taken from the Schofield 96 core showed the highest oil content, 65 per cent. of its total pore space being occupied by oil. Unfortunately, such samples give only an approximate idea of the actual oil content of the sand in the ground. They give a minimum figure and the actual oil content may

[6] C. R. Fettke: Core Studies of the Second Sand of the Venango Group from Oil City, Pa. Petroleum Development and Technology in 1926, A. I. M. E., 228.

be considerably greater. During the coring operation there is ample opportunity for a certain percentage of the oil to escape and be replaced by water. Some evaporation losses also take place while the samples are in storage, and there is a slight unavoidable loss after they are removed from the containers and crushed preparatory to testing. In the case of at least six out of eight of the samples tested, the latter losses were negligible inasmuch as the pore space was practically completely saturated with oil and water. Since both wells were drilled in areas not yet reached by flood waters, and the sand itself, except around the edges of the field, contains practically no salt water, it is safe to assume that the major portion at least of the water in the samples entered during the drilling operation. To what extent it has replaced oil is unknown.

TABLE 6.—*Oil and Water Content of Eight Samples from Summit G-4 and Schofield 96 Cores*

Position of Sample in Core, Depth in Feet	Density of Rock	Total Pore Space by Volume, Per Cent.	Per Cent. of Total Pore Space Occupied by Oil	Per Cent. of Total Pore Space Occupied by Water	Per Cent. of Total Pore Space Not Occupied by Oil or Water
Summit G-4					
1737.25–1737.92	2.266	14.8	51	49	0
1739.42–1740.08	2.257	15.0	48	52	0
1741.92–1742.58	2.245	15.7	44	52	4
1761.88–1762.54	2.335	12.4	43	57	0
1784.92–1785.58	2.331	12.9	34	38	28
1786.00–1786.33	2.298	13.7	41	39	20
1787.00–1787.33	2.360	12.8	45	51	4
Schofield 96					
1680.33–1681.00	2.085	21.8	65	35	0

In order to have a further check on the nature of the water in the core samples, the total soluble salt content of the sample from a depth of 1741.92 to 1742.58 ft. in the Summit G-4 core and from 1680.33 to 1681.00 ft. in the Schofield 96 was determined. Of the former, 200 g. yielded only 0.1120 g. of soluble salts and a similar weight of the latter, 0.1760 g. Even assuming that all of these salts were in solution in the water in the pores of the sample, the concentration in the case of the former would be only 1.5 per cent. and in the case of the latter 2.4 per cent. Clearly this water cannot be of connate origin, as typical connate water on the edges of the Bradford pool has a concentration of 12.6 per cent.[7]

[7] P. D. Torrey: Oil-field Waters of the Bradford Pool. A. I. M. E. *Tech. Pub.* 38 (1927) 4.

Practical Applications of Results

Core studies give one a much clearer conception of the exact nature of the sand than can possibly be obtained from the examination of ordinary drill cuttings. They show from just what portions of the formation production can be expected, and which parts are barren. Several cores taken from wells so located as to be representative of the whole property are of inestimable value in the interpretation of sand cuttings from all wells drilled thereafter on that tract, with reference to the proper placing of shots. Inasmuch as wells are spaced only from 100 to 200 ft. apart in flooding practice, as applied at Bradford, this item alone is of sufficient importance in many instances to warrant taking the cores.

While the data obtained on the actual oil content of the sand are not exact, they are of value for purposes of comparison. Gas pays and water-bearing horizons along which by-passing may occur can no doubt be detected if they exist, provided the core is analyzed with sufficient care. Knowing the total capacity of the reservoir from the porosity determinations, the percentage of this space actually occupied by oil in the core samples obtained gives a minimum figure which is no doubt exceeded by that of the sand as it exists in the ground. The writer does not believe, however, that there is any justification for the assumption that the entire pore space of the sand was necessarily occupied by oil originally, and that by deducting the quantity already recovered, that which still remains can be estimated. Inasmuch as the Bradford sand has produced little or no water, except around the edges of the pool, it need not be taken into consideration. Gas has always been produced with the oil, however, and there is the possibility that the gas was not all in solution in the oil originally or necessarily segregated in one part of the sand. Gas not in solution would have occupied part of the pore space and thus reduced the capacity of the reservoir for oil.

Porosity and grain size are undoubtedly the two most important factors in determining permeability. Of two sands of the same porosity, but composed of grains of different sizes, the one with the coarser grains will have the higher permeability. If the porosity is uniform and sufficiently high and the grain size is the same for all parts of the sand body, the flood can be expected to advance at about the same rate throughout the different layers and a maximum recovery will result. If variations exist in porosity, grain size, or both in different layers of the sand, the rate of advance will not be the same throughout, but the water will break through along the more permeable layers first. Once it has broken through along a particular stratum from one well to the next, more active circulation is established along that horizon and less water is available for the layers of lower permeability, so that considerable oil still remains in these layers at the time that the wells are aban-

doned, which would have been recovered if this difference in permeability had not existed.

Exact data on porosity and grain size are of importance in determining the spacing between wells, and in some instances in determining whether or not it is advisable to apply additional pressure to that of the natural pressure of the water column in the intake well.

In conclusion, it may be stated that if core studies are to be of most value to the operator, considerably more work on the correlation of the data furnished by such studies, with the actual results obtained in practice in different parts of the field, is necessary. Companies that have kept the most detailed records, including production of both oil and water for individual wells, amount of water taken by intake wells, rates of advance of water in different directions, etc., are in the best position to do this work.

DISCUSSION

V. C. Smith,* New York, N. Y.—I have been closely associated with the development of the cable-tool core barrel, particularly the Keystone. The first barrel was invented in 1905 and patented by Downie, Smith and Ransom in 1906. Due to its light construction it could be used only in comparatively soft formations. Later this was strengthened by the use of the offset cutter, and first used in petroleum development work by the Dutch Shell Co. Richard Airey, of that company, suggested the split core barrel, a very useful and notable improvement.

In 1925 the Keystone, in conjunction with a number of Mid-Continent producers, of whom particular mention should be made of the Phillips company, undertook to redesign the core barrel in order to facilitate its use in the oil fields. Two types were evolved: The saw-tooth cutter type, which has been very successful in giving high recoveries and continuous cores in the softer formations, and the type described by Professor Fettke, which should be used only for very hard rocks where cutter and breakage loss of the other type make its use inadvisable. Unfortunately, this latter type tends to give a biscuit type rather than continuous core. This fault is inherent, however, with this type. Using the saw-tooth type, one of the mining companies has taken about 19,000 ft. of core from shallow holes with a recovery of better than 95 per cent. and at a cost of less than 40 c. per foot.

In regard to water washing, when we first cored the wells in Oklahoma, near Bartlesville, we found that we would lose a large proportion of the oil due to water washing. We therefore eliminated the grip ring and used a tapered retainer; we also placed within the barrel a bag filled with stiff clay, so that it would ride on top of the core and prevent contact with the water. We further eliminated contact of the core with water to an even greater degree by advancing the inside core barrel to within $^3/_4$ in. of the point of churning, or even, in softer sands, ahead of the outer barrel. I believe from what Mr. McKee and Mr. Guidinger, and others, have told me that we have practically eliminated the water effect and I have frequently seen cores taken which on being removed from the pressure in the barrel would flow oil.

In connection with the appraisal of the oil sands, I believe this to be a very important point.

There is another thing, not touched on by Professor Fettke; that is, the actual structural relation in which the oil lies. We found that there was definite walling

* Geologist.

off by little vertical veins in some cases; and where ripple marks were present, or geological conditions of that general character, the oil tended to follow these in a very definite relationship. I had some specimens in which I formed cylindrical cores and put gas pressure behind them; I compiled the speed of migration and found great differences. All of these data are invaluable in connection with the application of pressure drive whether with gas, water or air.

There is a little more cost in coring and changing the core barrel over than there is in actual drilling and, aside from limestones, an addition of approximately 25 per cent. of the ordinary drilling cost will more than cover all the core cost in the average case. In some individual cases there have been lower running costs with core tools than with ordinary ones.

J. D. Sisler,* Harrisburg, Pa. (written discussion).—Very little core drilling has been done preparatory to flooding and repressuring in Pennsylvania. In the "five-spot" method of flooding large investment is necessary to recover oil in a short period of time. Operators minimize this cost as much as possible and have tried to get along without core drilling. The recent methods of coring described in Professor Fettke's paper have replaced the old method of diamond-drilling the entire well, and have reduced the cost of obtaining a core from \$2000 or \$3000 to \$300 or \$400. This reduction in cost has made it possible to core sands in conjunction with the drilling of oil or water wells at only a slight increase in cost.

Professor Fettke has outlined the benefits of core drilling. These benefits are realized more fully if the coring is done before or at the beginning of the flooding operations.

All of the cores of the Bradford sand have been valuable in determining the porosity and permeability of the sand and the saturation of the sand by oil and water. They will be still more important in other fields in Pennsylvania. The Bradford sand has lent itself to flooding successfully because it is comparatively regular in thickness, and its porosity varies but slightly. In general, sands in other parts of Pennsylvania are not nearly as regular in physical character. The porosity varies greatly within sands, and lenses and partings of shale vary much in position and thickness locally. Before a property can be flooded with maximum efficiency it is necessary to know the exact physical character of the sand and the mode of occurrence of the oil in it. The proper study of a sand core forecasts much about the future success of the flood. Parts of the sand may be flooded with water, and other parts may not. Other sands may contain a mixture of oil and water. A complete core study will determine approximately not only the porosity and size of grain of the sand but the percentage of saturation by both oil and water. A core study enables the operator to determine the possibility of a by-pass; it enables him to choose the proper place in the sand to shoot or to cement off.

The greatest value of coring oil sands in the future outside of the Bradford district will be in the old Venango oil pool in the vicinity of Franklin, Oil City, and Titusville. Secondary recovery is beginning in this district, and very little is known about the physical character of the sands. By proper coring some intimation can be gained as to whether flooding will be successful.

There is a possibility that core studies may reveal the secret of oil and gas accumulation which is so effectively hidden in the northwestern parts of the Pennsylvania oil and gas fields, where structure seems to play a very little part in the accumulation. The common theory is that porosity has played the important role. Sufficient core-drilling would possibly reveal some of the facts governing this accumulation, and it is

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certain that much would be learned from the physical character of the sands themselves which would lead to more definite identification of them.

C. R. Fettke.—I have recently had an opportunity to witness the taking of a core of the Second Sand of the Venango group near Oil City, Pa., with a Baker cable-tool core barrel. A $5\frac{5}{8}$-in. bit taking a 2-in. core was used. The sand occurs at a depth of 655 ft. at the place where the core was taken. The upper portion consists of alternating layers of fine conglomerate and very pure quartz sandstone which are pretty thoroughly cemented. Four days were required to core the upper 8 ft., at an approximate cost of $23 per foot. The company doing the coring used its own drilling rig. Apparently, the oil sands of the Venango group in Pennsylvania are considerably more difficult to core with the cable-tool core barrel than the Bradford sand.

Manufacture of Nitroglycerin and Use of High Explosives in Oil and Gas Wells*

By C. O. Rison,† Bartlesville, Okla.

(New York Meeting, February, 1929)

High explosives, particularly nitroglycerin, have been used in torpedoes for the purpose of shooting oil and gas wells for more than 60 years. The early history of the oil industry in Pennsylvania is not clear as to who actually torpedoed the first well, although in 1865 the Roberts Torpedo Co. procured a patent covering the process. Gunpowder was first used, although nitroglycerin was substituted shortly afterwards.

Wells are shot for the purpose of increasing the flow of oil and gas. A shot-hole in the producing horizon, with its contributory fissures and fractures, increases the area of and stimulates drainage into the hole. The shot-hole also acts as a collecting basin from which the oil is pumped. As a rule, hard or close-grained sands or limes are shot, other more or less porous and soft formations usually do not require shooting, and might be injured by blasting. Shooting is also resorted to in mechanical trouble such as straightening crooked holes, sidetracking pipe or tools, and for severing frozen strings of casing or drill pipe. Explosives are also used sometimes to extinguish oil or gas-well fires although that work, which involves unusual conditions and methods, does not properly come within the classification of oil-well shooting.

Some Factors to Be Considered in Shooting Wells

Although nitroglycerin has been used extensively for more than half a century in shooting oil and gas wells, there is still a great deal of uncertainty as to the proper method of shooting or the amount of explosive required to produce best results in a particular formation. The possibility of shooting unproductive or cavey formations above or below the productive horizons, shooting into lower water, destroying casing seats, and the splitting or collapsing of casing strings, are factors that require consideration.

The engineering departments of a number of the larger oil companies are making a study of methods of shooting, and the amounts of liquid nitroglycerin or other explosives required in shooting various productive

* Revision of paper presented by the author before Mid-Continent Section, A. I. M. E., Tulsa, Oklahoma, June 7, 1928.

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strata. However, it is not unusual for some operators to load the hole with as much nitroglycerin as can be contained in the shell of largest diameter that will pass down the hole, regardless of the character or productivity of the formation to be shot.

As a rule a well is shot by a torpedo company shooter who is entirely unfamiliar with the physical condition of the well beyond the meager information supplied by the operator at the time the shot is ordered. Oftentimes, haste in drilling prevents the proper testing, and subsequent logging of information, which would enable the operator to space or place the explosive charge more advantageously. Measurements vary, according to the methods used to obtain them, and the resultant discrepancies have probably contributed largely on the side of error. The only obligation of the torpedo company and its shooter is to explode a certain quantity of explosive between specific depths in the well, based on the measurements and determinations of the operator. The method of detonation is usually prescribed by the operator. As most operators have not made any study of shooting methods or quantities of explosive required and are anxious to stay as far away as possible from the dangerous proceeding, it is not infrequent that the production of a well is hurt, rather than helped, by an improper charge or misplaced shot.

Some operators have shot their own wells with more or less success, using either gelatin dynamite or straight nitroglycerin dynamite. However, this is not general except in isolated cases, such as in the Poteau gas field, Oklahoma. Employees of oil or gas companies may have watched the shooting of hundreds of wells and through their observations have become more or less familiar with, if not actually proficient in, many of the details involved. While the knowledge gained through such observations is valuable from the standpoint of education in field practice, it does not qualify them as to the intimate understanding of explosives and the precise technique which is required in the actual work of shooting an oil or gas well.

Several disastrous premature explosions as listed at the end of this paper, have emphasized the fact that inherently dangerous high explosives should only be handled by one whose skill and knowledge of them have come from long experience.

Present Literature on Nitroglycerin and Oil-well Shooting

The present literature, dealing with the subject of nitroglycerin, includes a considerable number of comprehensive technical works by eminent foreign and American authors[1] as well as countless numbers of

[1] H. Brunswig: Explosives. Translated by C. E. Munroe and A. L. Kibler. John Wiley & Sons, New York, 1912.

O. Guttman: Industrie der Explosivestoffe. Macmillan & Co., New York, 1895.

short papers by various equally prominent chemists and technicians on some particular phases of the manufacture. Most of the technical works are built up entirely from laboratory experiments and mathematical or theoretical calculations, and are beyond the understanding of the ordinary student. In common with the methods and processes outlined in the papers of chemists and technicians, the work of these authors has been conducted with exactitude as to methods and materials, and under ideal conditions. The technology is therefore valuable to the large-scale plants which are provided with laboratory facilities, but it is inapplicable in many ways to the operation of ordinary torpedo company oil-field plants, which are generally operated at small capacity and without the perfect refrigeration, reclamation, and laboratory facilities of the large plants.

Naoúm's new book referred to covers large-scale manufacture and properties of nitroglycerin and the nitric esters homologous with and related to nitroglycerin in a comprehensive manner. While Naoúm, like many other authors, writes from the standpoint of European practice, the student will find the translation to be an understandable source of information on the particular subjects named.

Although the general public, through a gradually increasing contact and use of blasting materials of lower strength, has developed proficiency in handling and application, it is not to be inferred that nitroglycerin can, or should, be handled by the same persons or in the same manner. Long experience, together with a religious regard for the dangerous characteristics of nitroglycerin, are the qualifications of the successful torpedo man. Consequently, the public interest may, perchance, have been benefitted through omission of detail in regard to some of the phases of manufacture or application by the various authors.

This paper should not be construed as an attempted textbook on the chemistry or manufacture of high explosives. Modern methods and practices vary according to plant conditions, facilities, and the intended use of the explosive. While nitroglycerin is manufactured in both the small field plant of the torpedo company and the large-scale dynamite plant, the facilities of the latter are modern and adequate. Their product, manufactured under ideal conditions and with exactitude, is usually utilized in the same plant in the manufacture of gelatinized explosives, dynamite, and powder. Consequently, the highly specialized manufacturing operations and practices of the large explosive plant places

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M. Eissler: Modern High Explosives. 3d ed. John Wiley & Sons, New York, 1889.

E. M. Symmes: Technology Involved in Commercial Production of Nitroglycerin. *Chem. & Met. Eng.* (1921) **25**, 831.

P. Naoúm: Nitroglycerin and Nitroglycerin Explosives. Translated by E. M. Symmes. The Williams & Wilkins Co., Baltimore, 1928.

it in a class of operations beyond the range of this discussion, except as it may be particularly referred to in the text.

The small torpedo company field nitroglycerin plant, in some remote place, presents a different aspect. It manufactures nitroglycerin only, and its hazards are multiplied many times by the human equation and the necessity of repeated handling in transportation and storage. Its sensitive product must be transported over miles of rough oil-field roads, and there again handled to the bottom of deep wells.

In his discussion of manufacturing operations, practices, and hazards the modern explosives engineer or technician has shown little interest in the methods of manufacture, handling, and application of nitroglycerin in the oil industry. This lack of interest has probably come from a lack of knowledge of the technique and the problems of drilling and oil production. Likewise, field production forces are neither explosives engineers nor oil-well shooters. From observation, they are acquainted with the accepted use and general application of high explosives, but are generally unfamiliar with all of the many precautions that must be religiously observed if any degree of safety is to be expected in their use and application.

One of the principal objects in the preparation of this paper has been to outline, in an abstract yet understandable way, the history and characteristics of nitroglycerin as well as the technique of manufacture and application in the oil industry. The author does not believe that the public is interested in nitroglycerin, except to stay away from it. Neither does the author think that the petroleum engineer or field men will be interested in nitroglycerin, or other high explosives, beyond the point of sufficient understanding to enable him to assist in a more safe and proper use of it in and around wells.

Stability of Nitroglycerin

The early technique, with reference to the manufacture, storage, transportation and handling of nitroglycerin, was necessarily crude and the difficulties of the rapidly growing oil-well torpedo business were many. Premature explosions, the ever-present hazard of the nitroglycerin manufacturer, oftentimes completely wiped out plants and personnel.

Obviously, if the explosive was to be efficient it necessarily had to be destructive, and sensitive as well. That realization, and the dangers arising from the human equation, influenced the manufacturers to work toward stability as far as possible. Improved present-day practice, with the safeguards which have been thrown around the oil-field nitroglycerin industry, has done much to lessen considerably the hazard involved. However, the toll of lives and property exacted in the comparatively larger number of explosions during the past year would indicate the need of continued study and research from the standpoint of chemical

reactions and equilibrium. Stability can not be hoped for in the product of an oil-field nitroglycerin plant where the efficiency of the washing and neutralizing process is determined by rule of thumb, rather than by simple recognized mechanical or chemical tests.

Instability of nitroglycerin (in the sense of being unsafe to handle or store), in a large measure the result of later chemical reaction of unneutralized acids, may cause decomposition and explosion. This chemical reaction would probably be aided by the high temperatures of summer months.

Premature explosions have occurred at torpedo company factories, storage magazines, in transportation vehicles on public highways, and at wells which were being loaded for shooting. Many of these disastrous explosions have, no doubt, been the direct result of carelessness or of some contributing act on the part of the person handling the explosive. Nitroglycerin is so completely destructive that it is impossible later to ascertain the exact cause of premature explosions, except by conjecture. A completely devastated area, marked by a deep cone-shaped crater, debris, and scattered bits of human flesh, usually pictures the terrible violence and destructiveness of the oily liquid contained in the bright and harmless-appearing cans.

Pure nitroglycerin, acid and moisture-free, should not deteriorate in proper storage. A sample of nitroglycerin manufactured by Ascania Sobrero in 1846, is still preserved at the Nobel Dynamite Works, Avigliana, Italy.[2] Frequent tests have shown the absence of free acid and time has not altered the explosive. Berthelot[3] kept a bottle of nitroglycerin for more than 10 years without its showing any signs of alteration.

History of Nitroglycerin

The high explosive industry, with its extensive manufacture and utilization of nitroglycerin in its various forms, had its inception in 1846. Ascania Sobrero,[4] an Italian chemist of the School of Mechanics and Chemistry, Turin, Italy, discovered the explosive now known as nitroglycerin in that year while experimenting with nitric acid and various organic materials. The product, a yellow oil, was extremely sensitive and exploded with great violence. At the time of his discovery, Sobrero called this compound "pyroglycerin," although in later years it has been referred to as "glonoil oil," "trinitrate of glycerin," "blasting oil" and nitroglycerin.

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[2] R. Escales: Nitroglycerin and Dynamite. Veit, Leipzig, 1908.

[3] M. Berthelot: Explosives and Their Power, 422. Translated by C. N. Halse. J. Murray, London, 1892.

[4] A. Sobrero: *Compt. rend.* (1847) **24.**

In the same year, 1846, C. F. Shoenbien of Basel, Switzerland, discovered nitrocellulose or guncotton by treating raw cotton with a mixture of nitric and sulfuric acid.

History[5] records the disastrous experiences of chemists who experimented with Sobrero's pyroglycerin, and the failure of the Imperial German Government which sought to replace black blasting powder with guncotton as a propellant explosive. The utilization of either nitroglycerin or guncotton as important technical explosives did not begin until about 20 years later. In the interim, a 1 per cent. solution of the nitrated glycerin in grain alcohol found a limited use in medicine as a heart stimulant.

Early Utilization of Nitroglycerin and Guncotton

In 1859, Emmanuel and Alfred Nobel, two eminent Swedish engineers, began to study and experiment with Sobrero's pyroglycerin which several chemists in 1854 (Williamson and Railton) had pronounced to be a trinitrate of glycerin instead of a pyroglycerin. In 1861, the Nobels, with the financial aid of Napoleon III and several French bankers, constructed a small experimental factory at Helenborg, near Stockholm, Sweden, and manufactured nitroglycerin. Although fuse was invented by Bickford in 1831, it would not explode the nitroglycerin and the principal difficulty of the Nobels was in finding a satisfactory means of detonating it in its original liquid form. Consequently, nitroglycerin was utilized by mixing it with black powder or guncotton in order to increase the power of those explosives.

Although mercury fulminate ($Hg(CNO)_2$) was discovered by Howard in 1799, and was used in gun caps as early as 1815, it did not become an important detonating agent until 1864. Nobel then enlarged these percussion gun caps in the shape of a long copper cylinder and filled them with mercury fulminate which, in effect, is the modern blasting cap. Recent practice, however, is to replace the greater part of the mercury fulminate with picric acid, trinitrotoluene, potassium chlorate, or other explosive compounds, leaving only sufficient mercury fulminate to act as a booster for the balance of the detonating charge.

On Sept. 3, 1864, the Nobel plant at Helenborg was destroyed by an explosion. In 1865, the concern of Alfred Nobel & Co. was organized

[5] For complete and detailed information regarding the discovery and early history of high explosives, the reader is referred to History of the Explosives Industry in America, by Arthur Van Gelder and Hugo Schlatter, Columbia University Press, New York, 1927. This work was prepared from data collected by, and published under, the direction of the Institute of Makers of Explosives. The work is instructive as well as historical, and has been freely drawn upon by the auther in preparing the paragraphs on the origin and early history of high explosives.

and a new and larger plant was constructed at Krummel, in Hanover. This concern and establishment is today the largest manufacturer of explosives in continental Europe.

Up until 1866, Alfred Nobel & Co. exported considerable quantities of nitroglycerin or blasting oil to other countries, particularly to the United States, for blasting in quarries and in the Californian gold fields.

First Use of Nitroglycerin in America

The first recorded use of Nobel's blasting oil occurred in New York on July 15, 1865, where a quantity was exploded in a borehole with a gunpowder primer and ordinary fuse. This explosive was imported from Hamburg by Otto Burstenbinder, acting as an agent of the Nobel concern. In 1865, Nobel personally demonstrated his nitroglycerin in a borehole in Noltes quarry, on 83rd St., New York City.

Because of the sensitive nature of the explosive, and the consequent hazards of transportation, its importation was restricted. A violent and destructive explosion occurred in New York on Nov. 5, 1865; this disaster was caused through the carelessness of some person who had left a case of the imported nitroglycerin in front of one of the leading hotels. Several other disasters occurred during the following year, one explosion completely wrecking the steamship *European* on April 3, 1866, while lying at its pier at Aspinwall, Panama. Seventy cases of nitroglycerin in transit to the goldfields of California exploded, killed 60 people and caused a property loss of more than $1,000,000. Several other disastrous explosions shortly afterward influenced the steamship companies to refuse to accept nitroglycerin for transportation from Europe and through the efforts of Alfred Nobel, the U. S. Blasting Oil Co. was organized in New York on June 27, 1866, for the purpose of manufacturing nitroglycerin in America for industrial purposes.

Soon after the completion of Edwin Drake's discovery oil well in Pennsylvania, George M. Mowbray erected an oil refinery near Titusville. Following the demoralization resulting from the wild speculation in oil in 1866, Mowbray discontinued the operation of his refinery and built the first nitroglycerin plants in America at North Adams, Mass., in 1867, and at Titusville in 1868. He successfully manufactured more than 1,000,000 lb. of this explosive at North Adams, the greater part of which was used in the construction of the Hoosac Tunnel. More than 100,000 lb. were also furnished from that plant and exported in a frozen condition, in a specially built car, for use in the construction of the Canadian Pacific Railway in Canada.

Although the U. S. Blasting Oil Co. manufactured much nitroglycerin after 1866 at its Ridgefield, N. J., plant, it granted licenses to various persons and concerns on a royalty basis. The first of these licenses recorded was on March 24, 1868, to Joseph P. Stewart. Subsequent

licenses were granted to Roberts Torpedo Co., composed of E. A. L. Roberts and Walter Roberts; March and Harwood, doing business under the name of the Marquette Nitroglycerin Co.; and to T. P. Shaffner, to operate under the Stewart license. In November, 1871, the U. S. Blasting Oil Co., T. P. Shaffner, and Joseph P. Stewart assigned to the Atlantic Giant Powder Co. a license grant for the entire United States under the Nobel patents which were owned by the U. S. Blasting Oil Co., all of Shaffner's patents, and all of the rights which Joseph P. Stewart had secured under his license contract.

In packing metal containers of nitroglycerin with kieselguhr, Nobel found that this material was a suitable absorbent for the liquid explosive which was so dangerous and inconvenient to handle by itself. In 1867, Nobel perfected and patented his combination of kieselguhr and liquid nitroglycerin which he called "dynamite." The first manufacture of dynamite in America, under the Nobel patents, was near San Francisco, Calif., in 1868.

First Nitroglycerin Plants Supplying Oil Industry

The first factory for the manufacture of nitroglycerin for the exclusive use of the oil industry seems to have been one constructed on Church Run, near Titusville, Pa., by Col. P. Davidson. This plant blew up on March 18, 1869, killing Davidson and all of his employees. Mowbray had built a factory in 1868 near the Davidson location, but probably on account of conflict with the basic patents of the Roberts Torpedo Co. procured in 1865, it did not operate long.

The third factory, established about 1868, was that of the Roberts Torpedo Co. In December, 1869, a violent explosion occurred in the Roberts factory, although it is not known whether Roberts actually manufactured the nitroglycerin which exploded, or whether it was part of a shipment received from the U. S. Blasting Oil Co.'s plant at Ridgefield, N. J., or from the Lake Shore Nitroglycerin Co.'s plant at Painesville, Ohio.

With the right to manufacture nitroglycerin under the Nobel patents, secured by license in 1871 from the U. S. Blasting Oil Co., and their basic patents on shooting oil wells procured in 1865, the Roberts Torpedo Co. assumed a dominant position in the oil-well shooting business for approximately 15 years. The established prices of the Roberts Torpedo Co., according to an advertisement which appeared in the Pithole (Pa.), *Daily Record*, Feb. 8, 1868, were as follows: For an 8-lb. shot, 2.42 qt., $150; for a 16-lb. shot, 4.92 qt., $200.

For a considerable period numerous individuals "moon-lighted" nitroglycerin shots at reduced prices and in violation of the Roberts patent. Extensive litigation over several years was finally decided in favor of Roberts, and the illicit sales were stopped.

Discovery of Blasting Gelatin

In searching for a substance that would "hold" the liquid nitroglycerin better than his kielselguhr absorbent, Nobel's experiments led him to mix from 7 to 10 per cent. collodion cotton with the liquid explosive. Slight heating resulted in a tough, plastic and elastic mass which did not exude the liquid explosive as did the other absorbents then in use. In 1875, Nobel perfected and patented the jellylike product which he called "blasting gelatin." This explosive had a tremenduous shattering power, was less sensitive than liquid nitroglycerin, and was more convenient to handle.

Manufacture of Nitroglycerin

Nitroglycerin Factories and Equipment

Liquid nitroglycerin, for use as such in the oil industry, is manufactured in plants operated by torpedo companies whose plants are conveniently situated with reference to magazine stations and active fields. The plant is always in a remote place, a site within a reasonable distance from a railroad being preferable from the standpoint of transportation of raw materials. The equipment of some field plants consists of a nitrator, a drowning or separating tank, a wash tank, several catch-basin tanks, and a neutralizing tank. In some plants, however, no neutralizing tank is used. This tank equipment is built on a series of terraces below the nitrator so that the movement of nitroglycerin can be obtained by gravity flow from the nitrator to the drowning tank and washing tank, etc.

The early types of nitrators were made of wood with a lining of some metal, such as lead. More recent types, including those used at the present, are constructed of steel and have refrigeration coils in them. Refrigeration is accomplished by the circulation of cold water, although in many large dynamite plants a calcium chloride brine is used in connection with compression refrigeration machines.

The contents of the nitrator are agitated during the process of nitration by a vertical agitator shaft operating on a bearing above and on the outside of the nitrating chamber. The agitator shaft is driven by a steam engine, but as continuous agitation is necessary to prevent decomposition and premature explosion during nitration, the agitator is equipped with a crank so that it can be operated by hand in emergencies. Nitrators in the larger plants are equipped so that agitation may be continued with compressed air in case steam-driven equipment unexpectedly goes out of service.

Materials Used in Nitration

The glycerin, $C_3H_5(OH)_3$, used is the so-called dynamite glycerin, a packing house or soap factory by-product. It is approximately 98.5

per cent. pure, has a specific gravity of 1.26 at 15°C., and ranges from water-white to straw color.

High-strength nitric and sulfuric acids are used, the exact proportion of each acid in the mixture depending on several factors from a chemical and operating standpoint. In commenting on one of the most important of these factors, Groggins[6] writes—

> it appears advisable to formulate the composition of the mixed acid so that a definite optimum relationship exists at the close of nitration between the sulfuric acid and water. This relationship is usually termed the D. V. S.—that is, the dehydrating value of sulfuric acid. It is expressed numerically by the quotient obtained from dividing the actual sulfuric acid content of the mixed acid by the total water present when nitration is completed. The latter figure includes, in addition to the water of reaction, the water that is introduced with the mixed acid and glycerin.

The acid mixtures used in torpedo company field plants vary, but in many cases, they are slightly higher in sulfuric acid and lower in nitric acid than the mixtures used under low temperatures in large dynamite plants.

Symmes[7] gives the percentage composition of a typical acid mixture used in a large dynamite plant as follows: H_2SO_4, 54.50 to 55.00; HNO_3, 42.50 to 45.25; $HNOSO_4$, 0.50 to 1.25; and H_2O, zero to 2.00 per cent. The nitration of 1300 lb. glycerin with 7000 lb. mixed acid of the above composition, at temperatures ranging from 34 to 45°F. should produce a yield of 231 parts of about 3000 lb. nitroglycerin. The theoretical yield is 246 parts, although that is never obtained in practice. Typical spent acids resulting from the nitration with such an acid mixture would probably have the following percentage composition: H_2SO_4, 75.90 to 76.60; HNO_3, 6.40 to 6.60; and H_2O, 17.00 to 17.30 per cent. The percentage composition of a car of mixed acids received in the field June 18, 1928, was 61.33 of H_2SO_4, 36.25 of HNO_3, 0.10 of $HNOSO_4$, and 2.32 per cent. of H_2O.[8]

As a rule, in the field plants of the torpedo companies the nitrators have a nominal capacity of 1500 lb. of mixed acids; that mixture nitrates from 225 to 288 lb. of glycerin according to the composition of the mixed acids. Inasmuch as the usual refrigerant is cold water, the temperature of nitration in field plants is seldom lower than 90°F. This high temperature is not conducive to high yields, the average probably being 210 to 225 parts of nitroglycerin to each 100 parts of glycerin used.

Because spent acids from these field plants are not reclaimed it is probable that a considerable portion of the lower nitrates of glycerin, such as trinitroglycerin, dinitroglycerin, and mononitroglycerin, are lost. These lower nitrates are soluble in the acid mixture and are

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[6] P. H. Groggins: Nitration: A Unit of Chemical Engineering. *Chem. & Met. Eng.* (1928) **35**.

[7] E. M. Symmes: *Op. cit.*

[8] Communication from E. L. Connolly, Larkin Torpedo Co., Tulsa, Okla.

drawn off with it. In the large plants the spent acids and lower nitrates are reclaimed, although, owing to the use of high-strength acids in a carefully regulated mixture under low temperatures, the production of soluble lower nitrates is probably restricted. This possibly contributes, in part, to the higher yields of such plants.

Ethylene glycol, a polyhydroxy alcohol, has been used in a few field plants during the last winter season as an admixture to glycerin in proportions of 25 to 50 per cent. for the purpose of lowering the freezing point of the nitrated product. The ethylene glycol is soluble in glycerin and nitration of the mixture is accomplished in the same manner a with glycerin alone. One large torpedo company is now privately experimenting with a 25 per cent. admixture to nitroglycerin which is thought to be either nitrobenzene or dinitrochlorohydrin.

Process of Nitration

In ordinary field plants 1500 lb. of acid mixture is run into the nitrator where its temperature is brought as low as possible by circulation of cold water. The glycerin is slowly fed into the acid mixture, being carried under the surface by the action of the revolving agitator. The tendency of the mass to heat is controlled by carefully regulating the inflow of glycerin. As nitroglycerin is lighter than the acid it comes to the surface as fast as formed. If agitation is not maintained during the entire process of nitration, portions of the glycerin may cause heating in the top portion of the acid mixture, which will result in decomposition and premature explosion of the entire charge. As a result of the chemical reaction which takes place between glycerin and nitric acid NO_2 groups replace hydrogen in the glycerin. The comparatively large quantities of sulfuric acid in the nitrating mixture combine with water as it is formed and prevent it from interfering with nitration. It is possible to obtain small quantities of nitroglycerin from nitration with pure nitric acid, although, due to the interference of water formed during the chemical reaction, the small yields would be unprofitable.

After nitration is complete, which usually requires less than 1 hr., the entire contents of the nitrator are run into the cold water contained in the drowning tank. At this time the mixture is slightly emulsified, although in the drowning tank the nitroglycerin rapidly separates and, being heavier than water, settles to the bottom of the drowning tank. The water and spent acids containing the soluble lower nitrates of glycerin are run through the catch-basin tanks into an acid pond. These tanks are settling basins for any nitroglycerin that might be carried out with the water and spent acid mixture.

The nitroglycerin is then conducted from the drowning tank by gravity flow to the wash tanks where is is mechanically agitated in warm

water having a temperature from 80 to 90° F. Minute quantities of fatty acid substances contained in the original glycerin produce "slime" during separation and washing. In this washing process all of the slime, and most of the remaining acid, are removed.

In some plants where a neutralizing tank is not in use the glycerin is washed several times with water and is immediately canned. Sometimes the last washing is in a solution of sodium bicarbonate.

In other plants the explosive is then moved by gravity flow to a neutralizing tank containing a solution of sodium bicarbonate, the temperature of which should range from 90 to 100° F. In this bath the remaining acid is neutralized, the agitation or washing being continued until an absolutely neutral test with litmus paper is obtained. The neutralizing bath should be in the ratio of 1½ parts of water to 1 part of glycerin, the water carrying at least 1½ lb. of sodium bicarbonate for each 100 lb. of glycerin to be neutralized. After neutralizing and settling, the finished product should not exceed 1 per cent. moisture and should be free of acid.

While at a temperature of between 60 and 90° F. the nitroglycerin is canned, 32.5 lb. being put into each 10-qt. can. The cans are made of heavy tin which has been treated with a zinc-lead coating. If nitroglycerin contains even small quantities of unneutralized acid this will attack the metal, particularly those having no protective coating. In a comparatively short time the acid will accumulate on top of the nitroglycerin and will eat pin holes through the walls of the can at the fluid level, thereby causing the dangerous "leaker."

In canning nitroglycerin it is often necessary to use cans which have previously been used. Before refilling a can, the residuum drained from it is carefully tested and if the test shows acid, the can is neutralized on the inside with a solution of sodium bicarbonate. In cleaning up nitroglycerin which has become spilled on the outside of cans, on floors, on machinery, and other places, a suitable solvent is first used as a neutralizing agent, after which it is thoroughly washed with warm water. Nitroglycerin is practically insoluble in water, and warm water alone will neither remove nor affect it.

In the manufacture and handling of nitroglycerin it is of the utmost importance that each employee keep foremost in his thoughts the axiom, "A glycerin man makes but one mistake." That mistake, if he makes it, is visited upon his fellow employees in the plant as well as himself.

Neutralizing Solvents for Nitroglycerin

Nitroglycerin is soluble in a number of substances which may be effectively used for the purpose of neutralizing the stain or remaining film

of nitroglycerin. The most common and easily obtainable of these are ether, denatured or wood alcohol, and chloroform. The Explosives Physical Laboratory of the U. S. Bureau of Mines has developed an effective solvent which is made up according to the following formula:[9] Water, ½ gal.; denatured or wood alcohol, ½ gal.; and sodium sulfide, 2 lb. In connection with the use of any particular solvent it should be understood that the neutralizing agent is not completely effective where nitroglycerin has penetrated or has been absorbed into wood floors or woodwork.

Characteristics of Nitroglycerin

Nitroglycerin, $C_3H_5(NO_3)_3$, is a heavy viscous oily liquid, ranging from colorless to straw color. It has a specific gravity of 1.60 at 15° C. and is not hygroscopic. It is slightly volatile and has a powerful physiologic effect. Merely handling it, or entering a building containing it, will usually produce a violent headache. Continued contact with it brings immunity, although if away from it a few days the immunity is lost. It is practically insoluble in water or oil, but is readily soluble in ether, acetone, ethyl and methyl alcohol, chloroform, benzene, phenol, glacial acetic acid and sulfuric acid.

Pure nitroglycerin crystallizes into hard prismatic needles at 12° to 12.5° C. In freezing it contracts approximately 8 per cent. of its volume and when frozen it has a specific gravity of 1.7.

Hazard of Freezing

The freezing of nitroglycerin constitutes an inconvenience and a considerable hazard. In large plants, where the product is for use in the manufacture of dynamite or other solidified explosives for industrial purposes, the nitrated polyglycerins and glycol have been used to form undercooled solutions which retarded freezing.[10] Admixtures, such as dinitrotoluol, trinitrotoluol, dinitrochlorohydrin, and other nitrated hydrocarbons, also have been utilized to lower the freezing points.

During the manufacture of nitroglycerin, the temperatures commonly employed during nitration in some of the large plants are below the normal freezing point of nitroglycerin. The reason why no freezing is experienced, particularly during nitration, is probably on account of the relatively large amount of acid in the mixture and the erratic characteristics of the chemical combination.

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[9] S. P. Howell and J. E. Tiffany: Methods for Routine Work in the Explosives Physical Laboratory of the U. S. Bureau of Mines. *Tech. Paper* 186 (1918). 63 pp.

[10] E. M. Symmes: Processes, Products and Personnel Link Explosives Manufacture to Other Chemical Engineering Industries. *Chem. & Met. Eng.* (1928), **35**, 234.

A. LaMotte: Development and Use of Industrial Explosives. *Min. & Met.*, (1924) **5**, 428.

Torpedo company field plants which manufacture nitroglycerin for oil-well purposes seldom use admixtures to prevent freezing. Nitroglycerin is very sensitive to rough handling, friction, or shock. It is not easily ignited by fire, although it is very sensitive to sudden heating. A small amount absorbed in blotting paper will burn and be consumed without consequences, but if any amount of nitroglycerin is ignited, it will explode violently when sufficient heat has been communicated to the mass to cause decomposition. Berthelot[11] states that electric sparks inflame nitroglycerin, though with difficulty. Under certain conditions, they may cause it to explode; for instance, under the influence of a series of strong sparks nitroglycerin changes and turns brown, then explodes.

Explosive Gelatin or "Solidified" Nitroglycerin

This explosive is properly designated in technology as explosive gelatin, although, in connection with its use in oil-well torpedoes, it is usually referred to as solidified nitroglycerin. In making comparative tests of other high explosives, the results are usually classified, using the properties of explosive gelatin as 100 per cent.

The manufacture of solidified nitroglycerin is accomplished by gelatinizing liquid nitroglycerin with a certain grade of soluble explosive collodion cotton. The mixture, consisting of 90 to 97 per cent. liquid nitroglycerin and 3 to 10 per cent. soluble collodion cotton, is slightly warmed and agitated until it has become a transparent elastic mass having a density of 1.65.

The process of gelatinization is not new, it having been originated and used by Nobel in 1875. This explosive is not hygroscopic, leaves no solid residue on explosion, and does not exude liquid nitroglycerin in the presence of water or other liquids. It is less sensitive than the liquid nitroglycerin, although considerably more powerful. A strong detonator is required to explode it properly.

Gelatin Dynamite or "Torpedo Gelatin"

In connection with this discussion, it should be understood that gelatin dynamite, or so-called "torpedo gelatin," while manufactured in a similar manner, should not be designated as solidified nitroglycerin, except as to the amount of liquid nitroglycerin which has been gelatinized in it.

Unlike explosive gelatin, or solidified nitroglycerin, the composition of gelatin dynamite varies within wide limits as to its basal and constituent ingredients. A type of gelatin dynamite used extensively for torpedo work in Californian oil fields has the following percentage composition: nitroglycerin, 72; collodion cotton, 3; wood pulp, 14; and

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[11] M. Berthelot: *Op. cit.*

sodium nitrate, 11 per cent. Other types contain less nitroglycerin and may contain potassium nitrate or ammonium nitrate instead of sodium nitrate, and meal instead of wood pulp. The strength and classification of the explosive are largely governed by the amount of its gelatinized nitroglycerin base. This type of explosive usually contains nitrates which are hygroscopic. It is somewhat less sensitive than either liquid nitroglycerin or so-called solidified nitroglycerin, and, like the latter named explosive, it requires a strong detonator to explode it properly.

Storage and Transportation of Nitroglycerin

Factory or Field Storage Magazines

As a rule, the site of a magazine is selected with regard for both accessibility and safety. Topography is a large factor, a place surrounded by hills being preferable. The American Table of Distances governs the situation of a magazine, according to its intended capacity, with reference to habitations, highways, and railroads. The quantity of explosives stored in a magazine is kept at a minimum, consistent with the extent of operations in the area which it is intended to serve.

The Littleford steel magazine is a type commonly used. This is of bolted construction and may easily be dismantled and moved. An opening in the front gable, protected from rain, sun, and sparks supplies ample ventilation through an opening in the ceiling. Inside walls and ceiling are built in the magazine, and the annular space between these walls and the outside steel walls is filled with an insulating substance. Two shelves, supported by 2 by 4s, are usually placed along one side and one end of the magazine. These shelves are 2 ft. wide; the upper shelf being approximately 2 ft. above the lower shelf. The lower shelf is usually built 6 to 12 in. above the magazine floor.

Heating Magazines

Because nitroglycerin freezes easily, the magazine must be heated during certain seasons and a more or less even temperature maintained. Two methods of heating are employed. One is by the Hitchins hot-water heater. In this system the coal or gas stove, containing hot-water coils, is in a nearby building and the circulating system is connected to a water tank inside the magazine.

The other method of heating is by an open-flame, 2 or 3-wick, kerosene oil stove. This system, exclusively used up to a few years ago, has given satisfactory service when properly regulated in a well-ventilated magazine. If the magazine does not have sufficient ventilation the flame will smoke and the inside of the building will become covered with soot which presents a serious fire hazard as it may become ignited and cause an explosion of the magazine.

In view of the success and popularity of the Hitchins system it appears to be the most convenient and efficient manner of heating. The advantages of the open-flame stove as a producer of quick and even heat are overbalanced by the difficulties of proper regulation and attendant fire hazard. A leaking can of nitroglycerin being carried out of the magazine might allow the contents to come in contact with the open flame if the stove be burning at the time. The lighting of stoves in magazines requires the use of matches and this should be discouraged. A dependable Fahrenheit thermometer is placed in the magazine and amployees daily note the temperature, ventilation, and condition of the heating equipment.

If an open-flame stove is used it should always be extinguished by stock haulers or shooters before unloading or loading nitroglycerin into or from the magazine. If the fire is extinguished by a stock hauler who delivers stock to the magazine, he should not relight the heater. The employee or shooter in charge of the magazine should relight the heater, regulate the ventilation, and loosen one cork from each can of new glycerin stock received. In the cold months the cans are allowed to stand several hours in the heated atmosphere of the magazine before loosening the corks. This is for the purpose of allowing any nitroglycerin to thaw which might be frozen around or to the cork on the inside of the can.

Cans that contain nitroglycerin are placed on the magazine shelves in such a manner that they do not touch each other. It is important that an air space of at least ½ in. be left between the cans. As nitroglycerin may, under certain conditions, deteriorate in storage the older cans should be used first.

When empty cans which have contained nitroglycerin are returned to the magazine, the shooter carefully drains any residual nitroglycerin from each can and carefully inspects them as to evidence of leakage and their availability for reuse. The nitroglycerin recovered by the drainage of the empty cans is called "bones" by shooters. In accumulating bones, it is important that the can containing the salvaged material should not be filled beyond the point where sufficient room is allowed for the expansion of the explosive due to rising temperature.

After cans are completely drained and the "leakers" marked by a piece of soft rope securely tied around the handle, the empties are usually stored in a separate magazine or building.

Nitroglycerin is a viscous liquid, and even though cans are carefully drained there is sufficient explosive remaining on the walls to produce a disastrous explosion. The same applies to torpedo dump shells used in dumping charges of liquid nitroglycerin at or near the bottom of wells. Experience points to the fact that, from the standpoint of their liability to explode, empty nitroglycerin cans are dangerous and under no cir-

cumstances should empty cans be thrown away or abandoned. If necessity prevents the return of empty containers to the proper magazine, they should be blown up and completely destroyed in some safe place. The attendant danger of leaving full cans of nitroglycerin at any place except the proper magazine, is so great that torpedo companies generally are ever watchful to see that their prohibition in that regard is not violated.

As a rule, other classes of high explosives, such as explosive gelatin (solidified nitroglycerin), torpedo gelatin (gelatin dynamite), and dynamite are stored in the same magazine with nitroglycerin. Boxes of these explosives should be stored right side up, but in no instance should a box of any of these materials be opened inside of the magazine. These boxes should always be opened outside of the magazine, using a mallet and hardwood wedge.

Electric or common blasting caps are extremely sensitive to friction and shock and should never be stored in a magazine containing high explosives. The storage of other material, subject to spontaneous combustion, such as clothing, greasy rags and waste, is also prohibited. Auxiliary equipment, such as torpedo shells, torpedo anchors, torpedo reels and clamps, and torpedo dump shells should not be warehoused in an explosives magazine.

The fire hazard is carefully guarded against by the removal of grass and brush for a safe distance around the magazine and buildings. The magazine door, secured by an unusually heavy padlock, presents no invitation to enter, and appropriate signs usually warn the passer-by or trespasser of his dangerous surroundings.

Methods of Transportation

For many years nitroglycerin was transported to and from field magazines in horse-drawn vehicles whose size and capacity were governed by the service for which they were intended. Stock wagons, designed for the transportation of large quantities of nitroglycerin from factories to field magazines, were heavy and were equipped with a box securely anchored to, and covering, its entire bed. This box was divided into a large number of padded cellular spaces or compartments each space being large enough to accommodate snugly a 10-qt. can of nitroglycerin. The bottom of the cans rested on a bed of hay, or some other similar material, in the bottom of the box. The top of the box was protected with hinged lids.

Shooting wagons, designed for the transportation of relatively small amounts of nitroglycerin from field magazines to wells, were of the light buggy type. These vehicles were equipped with the same type of transportation box, but which contained only sufficient cellular spaces or

compartments to carry the number of 10-qt. cans required for the ordinary shot.

The danger resulting from leakage of nitroglycerin through the bottom of the cellular transportation box brought an improvement in the form of a tight metallic lining which covered the sides and bottom of the box. In later years, the motor truck and automobile have generally replaced the two types of horse-drawn vehicles, although the construction of the cellular transportation box equipment remains the same. The exchange of motive power presented several difficulties not previously experienced. One was possible short circuits resulting from a defective electric wiring system. To guard against stray electrical currents, as well as the results of leakage in transportation, a part or all of the padding from the sides of each cellular compartment in transportation boxes was replaced with a rubber "boot" or cell. These more or less resilient rubber cells have a wall and bottom thickness of approximately ½ in. and are just large enough to allow a 10-qt. can to be set down inside of it. As an additional precaution, a small chain is usually attached to the body of the car and is allowed to drag for the purpose of grounding stray electrical currents.

In unloading or loading vehicles used in the transportation of nitroglycerin, the cans of explosive are handled to and from a shelf alongside the transportation box, and firmly secured to the body of the car by bolts and braces. The bolt heads are countersunk but extend slightly above the top of the shelf. In case of short-circuited wiring they often become sufficiently charged to throw out a strong series of sparks when contact is made with a metallic object. The author has personally noted this in one instance where a nailed shoe heel came in contact with one of these bolt heads. To overcome this hazard the shelf is covered with sheet rubber, the covering being secured by short nails or tacks on the underneath side of the shelf. Sheet rubber deteriorates and it requires replacement as soon as it shows evidence of wearing through over the bolt heads.

Before a full can of glycerin is removed from the magazine it should be carefully scrutinized. If it is a leaker, the contents should be immediately transferred into either a new or good used can; where any evidence of liquid nitroglycerin on its exterior appears, it should be first washed off with a neutralizing solvent and then with warm water. If corks in glycerin cans are not kept loosened while in the magazine, and the stock is not acid-free, the cans may develop internal pressure. This condition is usually detected by the bulging appearance of the side walls of the can or, in extreme cases, by smoke coming from the can. The internal pressure of a bad can is best relieved by gently loosening one cork after the can has been laid down with the bottom end slightly elevated. This should not be done near a stove or an open flame. After the pressure

has been relieved, some water should be added to the can and then sufficient poured out to bring down the level of the contents to its proper height. A full, or nearly full, nitroglycerin can is dangerous and should never be transported or put into magazine stock, regardless of the fact that a portion of the contents may be water.

In loading cans of nitroglycerin it is important that the bottom of each can be examined to see that no sand or other abrasive is adhering to it. If it is necessary to carry dynamite for use in jack squibs, it may be placed loose in one of the empty cellular spaces in the transportation box.

After the required number of cans have been loaded into the transportation box, the tops of the cans are covered with a thick pad and the hinged lid is lowered and fastened. Whenever the trip to the well requires a long haul, particularly in the hot season, frequent examination of the load is advisable. The same rule of safety which prohibits the storage of electric or common blasting caps in field nitroglycerin magazines should apply to their transportation in transportation boxes with nitroglycerin. A safe piece of equipment for handling blasting caps can be made from a long strip of rubber from a discarded inner tube. Small pieces of rubber can be cemented on the strip to form individual pockets for each blasting cap. After a sufficient number of caps have been inserted, the strip may be rolled up and carried in the shooter's kit box with comparative safety, each cap being insulated by the rubber against electrical current and friction.

The rubber cells of the transportation box should be kept clean, and as one of the functions of the boot is to catch and hold nitroglycerin leakage from cans, they should be frequently examined to see that they are in good condition.

The transportation and storage of nitroglycerin is regulated by law in most states and severe penalties are prescribed for violations. It is dangerous, as well as unlawful, to transport nitroglycerin or empty cans within the limits of any city or town in Oklahoma,[12] the penalty of the law running against the persons responsible for its violation.

Transportation vehicles should be operated carefully and driven at a moderate speed. The probability of arriving late at a well does not justify the driver in exceeding speed limits, or give him any special right on the roads.

The degree of safety and security enjoyed by the torpedo companies and the public alike, incidental to the transportation of nitroglycerin on public highways, depends on the cooperation of both. The public is not interested, and properly so, in either the manufacture or the handling of nitroglycerin. However, it should be interested in its own safety and that safety can only come from the realization that nitroglycerin is both sensitive and dangerous. The author has several times driven an

[12] Revised Laws of Oklahoma (1910) **2**, Chap. 67, Art. x, 1878, Sec. 6968–6974.

automobile carrying nitroglycerin into the "rough" of open ditches in deference to the determination of drivers of other vehicles.

Shooting

Oil or Gas Sands; Reservoir Rocks

The practice of shooting oil wells for production is not general in all fields of the United States, it being confined to fields or areas where the sands are either hard or close-grained and offer unusual resistance to the free flow of oil into wells. Such fields or areas occur in Pennsylvania, Ohio, West Virginia, Kentucky, Indiana, Illinois, Kansas, Oklahoma, North Texas, Wyoming, and Montana. Shooting is also resorted to in these fields, as in California, for cutting off strings of pipe and to remedy mechanical trouble.

The term "sand" is applied generally to all types of rocks which serve as natural reservoirs for oil or gas. In most American oil or gas fields these reservoir formations are either sandstones, conglomerates, limestones, or so-called granite wash. Occasionally, oil is produced from shales, but such instances are comparatively rare.

The reservoir formation or zone may be broken by interbedded streaks of other formation which condition may or may not be uniform over the entire field or area. The thickness of the reservoir zone may vary within wide limits within particular areas, and when structurally high, the upper portion of the zone may contain only free gas. In certain areas a part or all of the zone may be so affected by local cementation or gradation that it may be barren or have varying factors of productivity depending on effective porosity and texture. Obviously, the sand zone may be comparatively thick, yet practically all of the oil production may come from one or more relatively thin sections. The so-called "big pay" of certain flowing wells is probably from a few feet of sand having a high porosity and rather loosely cemented together; although this does not necessarily mean that the amount of oil contained in the remaining tighter portions of the saturated thickness of sand is inconsequential. The porosity of the big pay may be much higher than the remainder of the productive portion of the sand, but the total oil content may be much less. After shooting, the tight sand may respond to the extent that practically all of the production during the later life of the well will come from it.

Theory and Practice

Just why a shot in the oil sand should increase production of oil has never been definitely proved, but it is a rather generally accepted theory among operators that the stimulation is occasioned by a shattering of the oil-bearing formation, thereby creating fractures or crevices into

other accumulations of oil in the same or closely associated formation. Beyond doubt, drainage channels are often established by a shot, with other portions of the formation formerly closed by an impervious barrier or which have little drainage into the hole. The area of drainage from the face of the sand into the hole is materially increased by the cavity or shot-hole resulting from the shot.

The type of oil wells which are shot may be classified as:

(1) New wells in which the sand is either slightly saturated or allows more or less free oil to come into the hole; (2) wells which have produced naturally in a satisfactory amount since drilling in, without shooting, but which have since declined to the intermittent or head flow stage; (3) dry holes where shooting is done before the well is finally abandoned; and (4) old wells, previously shot, where production might be increased or further decline arrested.

As a reservoir zone may contain several breaks, some of which are shale, and the oil productive portion or portions be either hard, medium, or soft, the type of formations should be considered. This is particularly true where the entire zone consists of sand containing shale laminae.

As a rule, the more resistant oil-bearing rocks such as hard limestones and sandstones are effectively shattered by reasonably heavy shooting, whereas best results are usually obtained by shooting the softer limestones and sandstones with much lighter shots. As a rule, the more or less unconsolidated and soft sandstones are shot with light shots because heavy shooting may compact the sand and thereby retard production. For that reason the loose unconsolidated sands of the Californian and Gulf Coast districts, and the soft granite wash found in certain wells of Texas fields, are seldom shot to increase production. Although it is desirable that torpedo shells be anchored through breaks known to be nonproductive, particularly those of shale, it is obviously impossible to so space the explosive where the breaks are very thin or the productive zone is sand containing shale laminae. The latter type of sand is most effectively shot by regulating the size and distribution of the explosive charge according to the general character, hardness and known productivity of the zone.

Frequently, shooting is resorted to at intervals for the purpose of stimulating the production and natural flow of wells that have either "went dead" or developed a periodic head flow. These shots range in size from the squib of several quarts to the large 20 to 40-qt. shots. Some individual wells are shot two or three times during the period of natural flow, each successive shot being larger than the preceeding one.

When such wells cease flowing, and swabbing is necessary to obtain production, the practice is to shoot the entire section of productive formation before putting the well on either the air-gas lift or the pump. This method of shooting has attained wide use in fields where oil produc-

tion is by natural flow and it is not necessary to shoot for the purpose of obtaining a maximum initial production. The Cromwell, Papoose, and Seminole fields, Oklahoma, are recent examples of such fields.[13]

Shooting is resorted to in many wells where the more or less resistant rocks of the usually productive zone or other formation are barren. As wells of that type must be plugged and abandoned unless production can be induced by shooting, the amount of explosive used is usually more than would ordinarily be used were all or a portion of the sands productive.

Under certain conditions a light shot, properly distributed throughout the productive formation, is an effective method of arresting decline in production or removing paraffin and hard inorganic salt deposits from the face of an oil sand in old producing wells which have previously been shot. These light shots probably produce the combined effect of burning the paraffin and breaking down the face of the sand, although too heavy or too frequent shooting may enlarge the shot-hole to the extent that further shooting will be ineffective. As a rule, cleaning out is necessary after each shot, with the possible exception of light squib shots placed in head flow wells for the purpose of inducing continuous flow. The extent and duration of cleaning-out work depends on the character of the formation shot, amount of explosive used, behavior of the well following the shot, and the policy of the operator. By "behavior of the well" is meant whether the hole bridged or whether a part or all of the rock fragments were ejected by the explosion of the torpedo or the resultant flow of the well.

Several companies have experimented with wells in the Seminole field in an effort to reduce or entirely eliminate cleaning out and down-time after shooting by immediately putting them on the air-gas lift. Where it was possible to lower the tubing far enough in the shot-hole, all of the loose sand grains and finely divided particles of shale were ultimately washed out of the well by the flow of oil. The experiment was not a success from a mechanical standpoint because the larger fragments of shale or sand could not be removed in that manner and the bottom of the tubing was frequently plugged up in attempting to lower it through cavings in the shot-hole.

Preparing a Well for Shooting

After the producing strata have been penetrated to a sufficient depth, as in the case of a new well, the operator or his agent arranges with a torpedo company to shoot the well. The order for the shot specifies the

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[13] C. O. Rison and J. R. Bunn: Petroleum Engineering in Cromwell Oil Field, Seminole and Okfuskee Counties, Okla. Bur. Mines in cooperation with Office of Indian Affairs and State of Oklahoma, 1924.

J. R. Bunn: Petroleum Engineering in the Papoose Oil Field, Okfuskee and Hughes Counties, Oklahoma. Okla. Geol. Surv., in cooperation with Bur. Mines, 1926.

amount or number of quarts of explosive, diameter and length of torpedo shells, amount of common or loaded anchor required, and usually the manner of detonating the torpedo. The torpedo company's shooter procures the required amount of nitroglycerin, in 10-qt. cans, from its nearest field magazine and transports it, together with the empty torpedo shells, to the well in a shooting wagon. If, on arrival at the well, he finds that the work of shooting will be delayed, the shooting wagon is parked at a reasonable distance and where it will not be disturbed. Otherwise, it is carefully backed up to the derrick walk near the engine house. The shooter's reel, upon which is spooled more than sufficient small manila or wire line to reach the bottom of the well, is unloaded. The reel and line is used to lower loaded nitroglycerin shells, and so much depends on its efficient performance that the shooter will seldom let another use it.

Measurements Necessary in Shooting

The first steps towards shooting the well is to obtain and furnish the shooter with accurate information regarding: (1) Depth to bottom of last string of casing landed; (2) top and bottom of liner, if any has been set; (3) depth to top and bottom of producing formation; (4) whether the hole has any imperfections or reduced hole which might be liable to hang up a torpedo shell, or contains any cavings; (5) total depth of well; and (6) depth from the surface to the top of the fluid in hole. Provided that a recent measurement of the total depth can be verified to the satisfaction of the operator by running the bailer, the hole usually is not remeasured. It is not good practice to attempt the verification of bottom-hole measurements before shooting by running the drilling tools as the weight of the tools would probably carry them to the bottom through cavings that otherwise would support either a bailer or loaded torpedo shell. Further, the drilling tools would probably go by an obstruction or imperfection in the hole which might be detected with a bailer.

In completing a new well, in which the producing formation is interbedded with shale breaks, it is often noted that the hole fills up with oil but which, when bailed out, is practically all "frog." Frog is the driller's interpretation of an emulsion consisting of oil, shale mud and drilling water, which is created by the churning action of gas in the hole. Experience has taught that casing collapse is the inevitable result of shooting in wells where a column of water or frog is allowed to extend up into the casing. This damage does not occur where the fluid column extending into the casing is all clean live oil. The explanation is no doubt represented by the relative compressibility of water and oil, the latter fluid column containing a considerable quantity of free and dissolved gases.

Before shooting, the well should be bailed until all thin mud or frog has been removed for the following reasons: (1) Casing collapse may occur if thin mud or frog is allowed to extend up into the pipe; (2) the

finely divided particles of clay may be compacted against a part or all of the face of the producing sand by the shot, thereby retarding oil production.

It should be remembered that oil-well shooters necessarily follow instructions of the operator, and place the shot in shells of certain diameter and between specified depths. Obviously, if the necessary information and well measurements are either incorrect or incomplete, the results of a misplaced shot should not reflect any blame upon the shooter who has followed the information supplied.

Equipment Used in Shooting

After the operator has determined that the hole is clear, preparations are made by the shooter to load the well. A heavy set of clamps, securely bolted to the spokes of the steam engine flywheel, are centered so that the shooter's reel will be supported alongside the flywheel on a line with the center of the crank shaft. The spindle of the reel is placed through an opening in the clamp and a jam nut is driven tight with a sledge hammer. The drilling crew may properly assist in any or all of these operations, but the shooter should personally assure himself that jam nuts holding clamps and reel are tight. An iron bar is usually placed under the crank shaft to prevent the engine from turning over and possibly causing a shell to get away while being lowered. The drilling tools are set on the derrick floor, about 12 in. from the control head on the bullwheel side, the top of the tools being inclined so that the stem leans in or against the temper screw slot at the end of the walking beam. It is good practice to nail sufficient blocking behind the drilling bit to prevent any possibility of the tools slipping at a critical time. A heavy pulley is lashed to the stem with rope about 5 ft. from the floor, the work of attaching the pulley being done by the shooter, personally. The manila or wire shooting line is then passed over the sand reel, alongside the edge of the headache post, and through the pulley lashed to the stem. The end of the line is run through the eye of, and attached to, a bronze or brass torpedo hook which is constructed so that it will unhook when a loaded shell reaches bottom, or when any great amount of slack is permitted in the shooting line. The slack in the shooting line then is taken up on the reel to the point where the torpedo hook hangs about 3 ft. from the derrick floor. After the brake on the reel has been tightened by the shooter, he should test the brake, pulley, and torpedo hook by bearing as much of his weight as possible on the hook.

Types, Construction and Capacities of Torpedo Shells

The shells ordinarily used are made from tinned sheet metal and are cylindrical in shape. A downward pointing, conical diaphragm is fitted into the top or loading end of the shell. For mechanical reasons this

diaphragm is perforated with several holes. The lower end of the shell is provided with a conical false bottom which tends to reduce the danger of shells hanging up or lodging in caves, on liner tops, or on the shoulders of reduced holes. The older type of shell had a single thin wall of tin with conical diaphragm and conical bottom. In lowering this type of shell, the deviation of holes from the true vertical, and long casing strings, may cause friction wear, heat, leakage and possible premature explosion.

To meet this difficulty, a so-called "double" shell is now furnished by torpedo companies. This shell is simply one shell built within another, the nitroglycerin being placed in the inner shell and water in the annular space between the two shell walls. Other types of shell, constructed of various substances, are manufactured, although not in general use.

The empty torpedo shells should be tested for leakage by filling them with cold water and permitting them to remain full until used. Shells are often transported considerable distances, and afterward stand in the hot sun during the summer months. The author has noted several instances where single-wall shells were hot enough to be uncomfortable to the hand. As the decomposition of pure nitroglycerin is aided or accelerated by moderately high temperatures, it will be noted that the loading of a warm shell with nitroglycerin containing traces of free acid might not be conducive to the safety of the operation. Therefore, filling the shells with cold water serves an important and double purpose. In testing shells for leakage before running, the inside of the single-wall shell should be filled with water, although, if the double shell is used, the water jacket only need be tested.

The construction of all shells is such that the conical bottoms fit into the conical diaphragm tops and a torpedo of the required length can be

TABLE 1.—*Length of Torpedoes, Based on Number of 20-qt. Shells of Various Lengths and Diameters*

Diameter of Water-jacketed Shells, In.	Diameter of Single-Wall Shells, In.	Length of 20-qt. Shells		Total Length of 20-qt. Shells to Nearest Half Foot								
		Ft.	In.	2	3	4	5	6	7	8	9	10
2½	2	31	6	63	94½	126	157½	189	220½	252	283½	315
3	2½	20	1	40	60½	80½	100½	120½	140½	160½	181	201
3½	3	13	9	27½	41	55	69	82½	96½	110	124	137½
4	3½	10	2	20½	30½	40½	51	61	71	81½	91½	101½
4½	4	7	11	16	24	31½	39½	47½	55½	63½	71½	79
5	4½	6	4	12½	19	25½	31½	38	44½	50½	57	63½
5¼	4¾	5	8	11½	17	22½	28½	34	39½	45½	51	56½
5⅜	4⅞	5	5	11	16½	21½	27	32½	38	43½	49	54
5½	5	5	2	10½	15½	20½	26	31	36	41½	46½	51½
5¾	5¼	4	9	9½	14½	19	24	28½	33½	38	43	47½
6	5½	4	4	8½	13	17½	21½	26	30½	34½	39	43½
6½	6	3	8	7½	11	14½	18½	22	25½	29½	33	36½
7	6½	3	4	6½	10	13½	16½	20	23½	26½	30	33½
7½	7	3		6	9	12	15	18	21	24	27	30

built up, without breaking the continuity of the explosive charge, by landing one loaded shell on top of another. The length of such a torpedo, according to the diameter of shells and amount of nitroglycerin used, is given in Table 1. If gelatinized explosive is used, the amount necessary to fill one 20-qt. shell would depend entirely upon the density of loading.

Common or Loaded Anchor

Anchors are tin tubes about $1\frac{1}{4}$ inches in dia. which are used either to anchor the bottom of the shot a certain distance above the bottom of the well, or to connect two segments of a torpedo which have been purposely spaced a certain distance apart to prevent shooting unproductive or cavey formation. The type of anchor which is attached to the first or lower shell, for the purpose of anchoring or supporting the charge a certain distance from the bottom of the well, is called a common anchor.

It often occurs that the productive formation is interbedded with shale or other barren strata. To shoot such a well, a sufficient number of loaded shells to cover the lower portion of the productive formation are placed in the usual manner, and the length of loaded anchor required to reach the lower shells is placed on the bottom of the first shell to be placed above the unproductive strata. This anchor is filled with nitroglycerin and acts as a support for the upper portion of the torpedo. It also serves as a "lightning rod," connecting the two segments together and insuring detonation of the lower portion of the torpedo. This type of anchor, unlike common anchor, is closed at the lower end. Both common and loaded anchor are manufactured in lengths of 20 ft., but in shooting it may be used in as short lengths as may be required. A downward-pointing conical tip is fitted on the lower end of all anchor used so that it will be kept centered in the hole during the lowering of the shell and anchor.

Loading Torpedo Shells with Liquid Nitroglycerin

If it be assumed that the shells have been tested to the satisfaction of the operator, the shooter attaches the required amount of anchor to the first shell and hangs it in the top of the casing or control head on the torpedo hook. At this stage of the work all persons, except the torpedo company's shooter, should retire to a safe distance. Should the shooter require assistance or material during the loading of the well he will no doubt ask for it at the proper time. The curiosity of spectators seems to be stimulated by the dangerous proceedings and for that reason they have been well represented in many of the casualty lists resulting from premature explosions of nitroglycerin at wells.

Two 10-qt. cans of nitroglycerin are removed from the cellular transportation box of the shooting wagon and carried upon the derrick

floor. The corks are carefully removed from the cans and are placed in a pail of water. These corks absorb considerable nitroglycerin and have a small quantity of it adhering to their underneath side when first removed from cans. Consequently, these corks are explosive and the possibility of either losing them in the hole or allowing them to come in contact with tools or the derrick floor, should be guarded against in the manner suggested. The water used in the pail for this purpose should not be poured out on the derrick floor or used to wash down a shell hanging in the hole. Minute quantities of nitroglycerin might separate from the corks and settle to the bottom of the water in the pail. The nitroglycerin is then poured slowly and carefully from the cans into the top of the torpedo shell until the fluid level in the shell is a little below the lower end of the conical diaphragm. Under certain conditions, nitroglycerin expands considerably, and were a shell filled close to the top of the conical diaphragm it is possible that sufficient frictional heat might be generated in lowering the shell through a deep crooked hole to cause its increased bulk to overflow before it reached the bottom. If this happened, it might cause an explosion which might destroy the casing and ruin the well.

If any of the explosive is spilled on the outside of the shell it should first be neutralized with a solvent substance and then washed with warm water: water alone will neither dissolve nor neutralize it. The empty nitroglycerin cans, with the corks replaced, are returned to the transportation box by the shooter before starting to lower the shell. Except for the time actually required to remove full cans or to replace empty cans, the hinged lid of the transportation box should remain closed.

Use of Explosive Gelatin or Gelatin Dynamite in Torpedoes

The type of torpedo shell used for gelatin dynamite is similar to the single-wall type nitroglycerin shell, except it has no false bottom or conical diaphragm. The equipment used, and the method of rigging up and lowering, are the same as for a nitroglycerin shell.

In loading a shell with explosive gelatin, or so-called solidified nitroglycerin, the shooter should first put in enough to fill the conical bottom of the shell. This explosive is in cartridge form and a convenient way of loading is to tie a sufficient number of the cartridges together to fit the diameter or mouth of the shell. These are shoved to the bottom of the torpedo shell with a wood tamping rod, this operation being repeated until the shell is filled to within 8 in. from the top. The last 8 in. in the top of each shell is usually filled with 60 per cent. nitroglycerin dynamite, which acts as a booster. Theoretically, weight for weight, this explosive is higher in ballastic power, calories of heat, and gases evolved than an equal amount of liquid nitroglycerin; consequently, in loading a 20-qt.

shell the torpedo company recognizes this calculation of increased power by using the liquid nitroglycerin equivalent of 57 lb. of explosive gelatin. The weight of 20 qt. of nitroglycerin, under ordinary conditions, is 65 lb. net.

The type of torpedo shell used for loading gelatin dynamite, or so-called torpedo gelatin, is similar to the shell used for explosive gelatin, or so-called solidified nitroglycerin.

As a rule, this explosive is manufactured in 50-lb. blocks. By means of a short steel cylinder, slightly smaller than the inside diameter of the torpedo shell, the gelatin is cut into cylindrical blocks corresponding in length to the thickness of the block of explosive. These cylindrical blocks are shoved to the bottom of the shell with a wood tamping rod, the operation being repeated until the shell is full. As a rule, the irregular pieces of explosive, resulting from the operation of cutting the block into cylindrical shapes, are used last to complete the filling of the shell.

During the loading of the shell from one to three cartridges of 60 per cent. nitroglycerin dynamite are distributed through the charge at intervals of from 1½ to 2 ft. to act as boosters.

While it is desirable that shells loaded with gelatinized explosives be firmly packed to exclude air pockets, this should not be overdone. Aside from the fact that too much tamping may reduce the sensitiveness, it must be remembered that gelatinized explosives are not insensible to abuse and rough treatment.

Gelatin dynamite, or torpedo gelatin, is manufactured and supplied to the trade on the unit basis of pounds, although torpedo companies handle it as "quarts," based upon the liquid measure capacity of the shell or shells used. Table 2 gives the approximate lengths of shells of various diameters.[14]

Table 2.—*Approximate Length of Shells of Certain Diameters Holding 50 Lb. of Torpedo Gelatin.*

Diameter of Shell, In.	Approximate Length of Shells Holding 50 Lb. of Torpedo Gelatin	
	Ft.	In.
2	26	3
2½	16	8
3	11	5
3½	8	6
4	6	8
4½	5	3
5	4	4
5½	3	7
6	3	1
6½	2	9
7	2	6

[14] J. Barab: Deep-hole Blasting. Pamphlet, 10 pp., Hercules Powder Co., Wilmington, Del., July, 1925.

Lowering and Placing Loaded Torpedo Shells

In lowering loaded torpedo shells the shooter slightly releases the brake on the reel, thereby allowing the shooting line to pay out slowly. In many wells, where the loaded shell can be lowered to place without difficulty, this operation presents no particular problem. However, in other types of wells, the proper manipulation and control of the loaded shell during its passage down the hole is governed by a number of factors. Steady or head oil flows, variable fluid levels, and gas pockets tend to make the work difficult and dangerous. If the well is making a steady flow of gas or oil the diameter of the shell that can be lowered, if at all, is governed by the amount of open flow and the inside diameter of the last string of casing in the hole.

In attempting to shoot a well where the above conditions must be combated, a certain and safe method is to try to lower a shell of the desired diameter filled with water. If it can not be successfully handled down the hole, shells of the next smaller diameter can be tried. In that way a shell of some diameter may be found that can be lowered against the flow.

Before shooting an intermittent head-flow well, the duration of flow and the interval between flows should be determined so that the loaded shells may be lowered while the well is heading up. If the interval between flows is irregular or too short for safety the flow is often "killed" to permit shooting.

Killing a well is accomplished either by shutting or pinching in with a master gate, or by pumping oil or water in hole. Porous oil-producing strata will often take oil or water when the hydrostatic pressure of the fluid column exceeds the natural rock pressure in the formation. Therefore, it is inadvisable and unnecessary to put in any more fluid than actually required to stop the flow temporarily. The detrimental effects of water on a producing formation are well known and ordinarily it should not be used for the purpose of killing a well.

It is obvious that the manner of loading torpedo shells with nitroglycerin previously outlined can not be followed if the shells are intended for use in a gas well or a well having a steady oil flow. In such conditions the empty shells are either suspended or stood in the cellar for the purpose of loading. The loaded shell is then raised, placed in the hole on the torpedo hook, and immediately lowered.

The operation of lowering loaded shells into wells having a steady or head-oil flow requires both experience and ingenuity. The shell, once started down the hole, must be lowered slowly with a taut line. The progress of the shell downward is either retarded or accelerated, as the case may be, by irregularity in volume and pulsation of flow, heaving of the fluid by gas, and gas pockets. To prevent the shell

from becoming unhooked and "getting away," the travel of the shooting line into the hole at the surface must be regulated by the more or less irregular progress of the shell down the hole. By keeping the line taut the shooter is materially assisted in his work by the normal stretch of the line, which automatically "takes up," if the weight of the shell on it is reduced either by increased volume of flow or heaving fluid. By sense of touch on the shooting line the experienced shooter is able "to feel" a mental picture of the operation.

If a shell should become unhooked as a result of lowering too fast, in a flowing well where there is little or no pulsation in the more or less steady flow, it is probable that it would "float" to bottom without consequence. On the other hand, if the line has been kept taut and the shell should be unhooked by a pulsating or increased volume of flow, it is possible that the shell may be ejected from the well.

In the case of an intermittent head-flow well the shell may be unhooked by the heaving of the fluid in the well during the heading-up process. Variable fluid levels are characteristic of head-flow wells, the continuity and density of the heaving fluid column being interrupted by pockets of expanding gases. If a shell becomes unhooked and falls through a long gas pocket it probably would result in the explosion of the shell and destruction of the casing.

The practice of intentionally unhooking and "floating" shells in the hole, as in the case of an inactive well or one that is partly or completely filled with fluid, is an uncertain and dangerous manner of placing a torpedo.

When the first shell is landed, the line should be "flagged" at the surface for the guidance of the shooter in landing subsequent shells. After a shell has been landed, the brake on the reel is applied and the shooting line is pulled out of the hole and spooled by engine power. Sometimes it is difficult to determine whether or not a shell has been unhooked and for that reason it is always advisable to "feel the weight" of the shooting line before it has been pulled out of the fluid. In withdrawing the line from the hole, it is good practice to stop the engine and spool the last 200 ft. by hand. That amount of line should be marked off by a permanent "flag" which can be easily recognized. If this is watched for, and the remaining line spooled in by hand, it will eliminate the possibility of pulling a loaded shell up against the pulley. When possible to do so it is advisable to measure to the top of each shell placed, using a cage weight and steel or aluminum measuring line. To ensure accuracy the line used should be one which has been checked by a sand line or drilling cable and previously used in obtaining measurements of the oil-producing formation in the same well. If, for any reason, the steel line can not be run, a measurement can usually be taken to the top of the first and last shells with a light

bailer on the sand line. The dart should be properly protected and great care should be taken to "only touch" the shell; otherwise, the shells and anchor may be collapsed. This method of measurement is dangerous and should not be employed except when absolutely necessary.

Loaded shells sometimes lodge in the open hole and in such cases, when the shells contain liquid nitroglycerin, they must be "bled" so they can more safely be fished out. In bleeding the shell a sharpened tool, like a polish rod, is lowered on the sand line to pierce the shell. This allows the explosive to run out and settle through the fluid to the bottom of the hole. The practice of using a muffled bailer to shove down a shell which has become lodged in the hole is dangerous and should be discouraged.

In certain areas it is necessary to land the oil string at or near the top of the oil-producing formation in order to case off a large volume of gas in the overlying strata. The oil string, being too close to the sand to allow shooting without damage to the casing, is often pulled up or entirely out after the torpedo and detonator have been placed. Unless the casing has been unseated to allow the gas to flow during the loading of the well, the later sudden release of pressure may pick up and eject a loaded shell from the hole if the top of the shot be near the casing shoe.

A loaded shell ejected from the hole at high speed by high-pressure gas or a violent head flow of gas and oil invariably results in a destructive explosion. Despite the reports to the contrary, regarding the ease with which ejected shells can be caught at the surface, the author has not attempted to catch one and knows of no one who has. A loaded shell occasionally comes up on a more or less weak head flow and many times they have been successfully taken out of the flow at the control head without much difficulty.

In extreme cases the loaded shells and time bomb may possibly be lowered separately into a large flowing well on a wire line running through a lubricator on top of an upper master gate. After the loaded shell has been placed in the lubricator and the wire line stuffing box is in place, the lubricator should be poured completely full of oil. The flow of the well should be restricted by pinching the flow line about 5 min. before the master gate is slowly opened to equalize pressure and permit the downward passage of the shell. In lowering the shell, which should be done very slowly, care should be taken to prevent it from hanging up at master gates or flow into connections.

In the fields of high-flush production, competitive drilling and production campaigns have been responsible for the shooting of flowing wells in the early stages of high initial production. That it has been successfully accomplished by usual methods and has been beneficial in some cases, is not to be doubted, although there is grave doubt that all such wells can be shot with the same results.

The work of lowering loaded shells into large gas wells or flowing oil wells involves so much hazard to life and property that torpedo companies do not assume any responsibility. The technique and methods used in placing shells in wells where unusual conditions obtain are outlined herein as general information, not for the purpose of advocating the application of any particular method to any particular situation or well. It is certain, however, that the slightest deviation from technique and methods permitted by the sensitive characteristics of high explosives will bring quick and disastrous results.

Placing Nitroglycerin with Dump Shell

In some wells where the formation to be shot is extremely hard, and the operator desires to shoot with as much nitroglycerin as the hole through the horizon will hold, a dump shell is used in placing the explosive. This shell is made from heavy tinned sheet metal, about 7 ft. in length, and usually has a capacity of 20 qt. The lower end is provided with a conical false bottom which is perforated with a number of ½-in. holes to allow the explosive to drain through it when the shell is dumped. A round hole in the bottom of the shell is closed by a conical rubber valve attached to the lower end of a dump rod which extends up inside to the top where it is looped around the bail of the shell. The length of the loop permits sufficient travel of the rod to open the dump valve before the lower part of the loop comes up against the bail.

In using this shell an ordinary torpedo hook is attached about 4 ft. above the end of the shooting line. The 4 ft. of line below the hook is securely tied to the looped end of the dump rod, any excess line being loosely placed inside the top of the shell.

The mechanical operation of filling and lowering dump shells is the same as previously outlined herein to cover the loading and lowering of torpedo shells loaded with liquid nitroglycerin.

When the dump shell is landed on the bottom, the hook is detached and the dump valve is opened by picking the shell up off the bottom with the dump rod. After the shell has been allowed to drain it may be slowly pulled out of the hole, the entire operation being repeated until sufficient explosive has been placed.

It is obvious that if more than one run is made to bottom with a dump shell, the subsequent runs must be landed on bottom in nitroglycerin which has previously been dumped. This might allow sufficient explosive to adhere to the outside of the shell to cause a disastrous explosion while pulling it from the hole. From the standpoint of safety it is advisable first to place as many loaded torpedo shells as is required to extend up through the desired thickness of formation and then, if necessary, use a dump shell to place sufficient additional explosive in the annular space between the shells and wall of the hole.

Dump shells should be carefully handled after each run, and if they have been dumped on bottom in nitroglycerin, the entire exterior of the shell should be sponged with neutralizing solvent and afterward washed off with warm water.

This method of placing nitroglycerin is dangerous, particularly so in deep wells where casing strings are long and there is a possibility that there is considerable deviation from the true vertical. Other disadvantages of this method of shooting are: (1) possibility of fusing or "burning" the surface of the formation in contact with the explosive to the extent that the fused or "burned" surface may be impervious, and (2) possibility of shooting into so-called base or bottom water.

Pulling Casing Strings, or Liners, after Placing Torpedo

After a torpedo and detonator have been placed, it is often necessary to pull a casing string or liner up, or out of the hole, for the reason that it is too close to the sand to permit shooting without damage to the pipe. If this is to be done it is assumed that the operator has first unseated or loosened the casing or liner before starting to load the well and has made sure, in case a time bomb has been used, that it will allow him sufficient time to do the work.

As a rule, the pulling of a casing string or liner allows the formation to cave in, completely burying the torpedo and detonator. After the torpedo has been detonated the well must be cleaned out to remove the shattered rock and sand which has been broken from the walls of the hole by the explosion. If the condition of the hole permits, the string of casing or liner is immediately rerun to its seat; otherwise it is run in the hole as far as possible, and "carried" down by stages as the work of cleaning out progresses below it. Cleaning out is required, regardless of the method of detonation, or the fact that it has been unnecessary to pull up or remove the pipe for the purpose of shooting.

In the discussion of pulling casing or liners after a torpedo and detonator have been placed, it should be understood that the word "detonator" is intended to mean any method, or device, which can be controlled or regulated as to the time of its explosion. Obviously, such a detonator may be found in either the electric time bomb, mechanical time bomb, or electric wire line squib. However, it is impossible to run tools in a well after an electric wire line squib has been placed without damaging the lead wires. The abrasion of insulation of the wires is liable to result in a short circuit and the failure of the detonator to function. Therefore, the use of this squib precludes the possibility of pulling the liner with a casing spear, or of swabbing or bailing the well after the torpedo and electric squib have been placed. Casing strings may, under certain conditions, be successfully stripped up over the lead wires. If the lead wires were damaged during this operation the buried torpedo could not

be exploded, and unless a sufficient heat or chemical reaction was generated in the bottom of the well to promote decomposition and explosion, a dangerous cleaning-out job might result in the loss of the tools and perhaps the well.

Methods of Detonation

After the torpedo has been placed, it must be properly detonated. Nitroglycerin is typical of the nitro-group explosive, in that the molecular structure of nitric esters is rather loosely bound together. The initial impulse, necessary to cause an explosion, is transmitted most effectively to this type of explosive by a detonator. This detonator should be mercury fulminate, alone or by combination with a small amount of some type of nitro-group explosive. Proper detonation probably results in the breaking apart of the molecules and no doubt has considerable to do with the effectiveness of the resultant explosion.

Various methods of detonating torpedoes, such as sand firing head, jack squib, bumper squib, line squib, electric squib, and time bomb have been advanced and widely used.

The time bomb, originated in 1920, filled a want created by the many difficulties of safely placing and exploding the various modifications of the squib in deep wells, although it did not come into general use until several years later. For a time, torpedo companies and producers looked upon the earlier types of electrical and mechanical time bombs with suspicion, regarding them as "infernal machines." In the light of subsequent accidental explosions of the earlier types it appeared that the devices had probably been well named. As a result of keen competition among various manufacturers, many improvements have been made in electrical and mechanical time bomb equipment during the past several years. While the use of the time bomb has since become more or less general, particularly in deep wells, the various modifications of the squib are still used for special purposes and in shallow wells. For that reason the various methods and devices will be discussed separately.

After a time bomb has been lowered the casing can be swabbed, if necessary, to lower the oil column or to remove any water that may have been put in from the top, or any water which may have entered the well from the oil-producing strata. If the well is to be shot through the casing, all water should be removed to a point not less than 25 ft. below the shoe of the last string of casing. As the operation of a swab below the casing shoe is unsafe, a bailer should be carefully used for this purpose.

In the Seminole field, Oklahoma, it has often been possible to induce natural flow with the casing swab before the bomb exploded the torpedo. Care should be taken not to get a swab overloaded and hung up in the casing over a shot. A type of swab that will unload automatically if overloaded is preferable. To avoid the possibility of being caught coming

out of the hole when the torpedo is detonated, the tools should be removed from the hole at least 30 min. before the calculated time of explosion.

Zero-hour Electric Time Bomb

The zero-hour electric time bomb embodies the combination of a watch, a small dry-cell battery, two electric blasting caps, and $1\frac{1}{2}$ lb. of nitroglycerin dynamite or gelatinized explosive. The watch, battery and electric blasting caps constitute the elements of an electric circuit and are connected in such a manner that the hour hand of the watch, of positive polarity, functions as a switch for closing the circuit. A firing pin of fine wire, negatively connected through two electric blasting caps, and extending through the crystal of the watch, acts as the stationary portion of the switch. The minute hand of the watch is shortened sufficiently to avoid contact with the firing pin. Consequently, the hour hand is the only movable positive element capable of making contact with the fixed negative firing pin, and thereby closing the circuit which will explode the electric blasting caps.

The firing point, 12 o'clock on the ordinary watch dial, is indicated on the anticlockwise bomb watch dial by the letter *O*. The interval desired to elapse before the explosion occurs is fixed by setting the hour hand back from *O* the desired number of hours and minutes up to a maximum of 22 hr. The electric caps are then connected to the bomb terminal wires, after which the watch, battery, caps and dynamite are enclosed in a triple-compartment, cardboard case, of proper size to fit snugly in the cast-iron container. The case is intended to serve as a protective covering for the various elements, holds them firmly in their proper relative positions, and insulates them against external electrical influences. The upper hard rubber end of this case is a circular plate with a hole in the center, through which the watch stem protrudes. A semispherical cover of the same material, attached by a hinge and fastened shut by a snap latch, affords convenient access to the stem for winding and setting the watch without opening the cardboard case, and without chance of disturbing the fixed position of the watch, or its connection to the other elements. Likewise, when snapped shut over the stem, this cap prevents any possible inadvertent change in the watch setting, or any external contact with the positive terminal of the battery.

The cast-iron shell, closed by means of a threaded cap and lead gasket, is constructed to withstand an external pressure of at least 2000 lb. per square inch.

The loaded bomb is then enclosed in a short tin shell and lowered on the shooting line to the top of the nitroglycerin torpedo. The explosion of the bomb shatters the cast-iron shell to small bits and detonates the nitroglycerin torpedo. The high temperatures obtaining in the lower

part of deep wells do not seem to interfere with the efficacy of the bombs, although sometimes it has slowed the watches up 5 to 10 minutes.

These bombs are obtainable in two types, exactly alike in every particular, excepting the watches. In the standard type, most commonly used, the watch is of the ordinary type of movement, wherein the hour hand makes a complete circuit of the dial in 12 hr. The setting range of this type is, therefore, 1 to 11 hr. In the special 22-hr. type, for use where it is desired that more than 11 hr. shall elapse between the time of setting and the explosion of the torpedo, the watch has an especially constructed movement, wherein the hour hand moves at only one-half the speed of that of the ordinary watch, thus taking 24 hr. to encircle the dial. This type, therefore, may be set for 12 to 24 hours.

Where a shell of smaller diameter is required to run through casing less than 5 in., or in wells flowing under heavy gas pressure, a special seamless-steel tubing shell of 2½ in. outside diameter and 19 inches in length is used instead of a cast-iron shell. This tube is fluid and pressure proof, but it is not as frangible as cast iron and therefore is not quite as completely demolished.

Bolshevik Mechanical Time Bomb

The "Bolshevik" bomb is one of the two types of mechanically operated time bombs which are in general use as detonators. Both types are actuated by clocks and although the construction of the firing mechanism and arrangement is varied in one type, the same mechanical principle is utilized.

This time bomb consists of a small alarm clock, a brass cage equipped with a metallic hammer and firing pin, a tin tube for holding explosive, and a cast-iron shell capable of withstanding high fluid pressure. The metallic hammer, operated by the tension of a mousetrap spring, is "cocked" back, being held in firing position by several turns of a releasing screw, which has a deep slot in the top and extends a little above the top of the brass cage. Two firing pins, in a vertical position, are placed under the hammer in two small holes which extend through the base of the brass cage. The bottoms of the firing pin holes on the under side of the brass cage are enlarged and threaded to receive two short brass tubes about 1½ inches in length. The inside diameters of the tubes are machined to receive No. 6 common blasting caps. Two heavy gun caps are fitted inside the threaded ends of the tubes, in much the same fashion as a cartridge is fitted in a gun barrel. The tubes are then screwed into the enlarged firing pin hole, which allows the firing pins to rest on the top of the gun caps.

An important part of this bomb is a safety device attached to the clock. This device consists of a bar sliding in two bearings mounted on the back of the clock, fitted with a hoe-shaped element at the end of

the bar adjacent to the time winding key of the clock, and in line with a hole drilled through the alarm key stem. By pushing the end of the bar through the hole in the alarm stem, the latter is so locked that it can not operate for a period of 40 min., when the shooter has sufficient time to load the bomb and lower it to the bottom of the deep well. The bar is released from the safe position above indicated by the slow turning action of the winding key upon the hoe-shaped element and which slowly withdraws the bar from the locked or safe position. This takes one-fourth revolution of the winding key stem and requires 40 min. for the operation. This safety device is not easily jarred out of position after it has been set.

The clock and brass cage are attached together as one unit by means of two small screws. The upper end of the tin tube holding explosive fits the outside of the bottom half of the firing cage and is crimped rigidly to it by bending over two projecting metal ears. With the proper loading of the tube, the level of the explosive is such that the blasting caps are embedded in the top of the explosive. The entire unit is then slipped into the shell, care being taken to see that there is no dirt or other material inside the shell to prevent the assembly from reaching its proper position.

The cast-iron shell, closed with a screw cap and fiber gasket, is lowered into the well in the same manner as a loaded shell. When the alarm goes off, the tension of the clock spring backs out the set screw holding the hammer, thereby allowing the hammer to fall and drive firing pins into the detonating caps.

Several types of this bomb are manufactured for oil-well shooting, the variations being in outside diameter, construction of the shell, and number of operating mechanisms contained in the single bomb shell.

The so-called "twin" types contain two complete operating mechanisms in one shell, each consisting of clock, cage and explosive tube. Twin types are manufactured in different diameters, the first known as the "Regular Twin Bolshevik," with an outside diameter of 3⅜ in., a length of 34 in., and weighs 38 lb. This diameter permits the use of cast iron for the shell. Another twin type, known as the "Baby Twin Bolshevik," has an outside diameter of 2¾ in., a length of 36 in., and weighs 25 lb. The shell of this bomb is of Shelby seamless tubing, having cast-iron top and bottom caps. The smallest type is known as the "Baby Bolshevik." This bomb has a diameter of 2¾ in., a length of 16 in., and weighs 12 lb. The shell of this bomb is made of Shelby seamless tubing with top and bottom caps of cast iron. This bomb is equipped with a single operating mechanism. The Baby Bolshevik and Baby Twin, having small external diameters, are intended for use where, owing to the small inside diameter of the casing or extreme oil or gas pressures, the running of the larger types would be difficult or impossible.

King Mechanical Time Bomb

The King mechanical time bomb, while embodying practically the same mechanical principles of other types of mechanical bombs, is more compact in that the firing mechanism is permanently attached in proper position on the back of the clock. The metallic hammer, after being cocked back, is held in firing position by a trip spring which control is held in neutral position by a hook on the alarm winding key of the clock. Unlike other types, this device has no separate firing pins. A sharp pin, set permanently in the hammer, serves the purpose of a firing pin. In the operation of the King bomb the mechanical action of the clock and firing mechanism are utilized to ignite a 12-in. length of fuse to which common blasting caps are attached. When the alarm goes off it releases the trip spring controlling the hammer and permits the hammer to fall upon a fulminate gun cap set over an exposed section of water-proof fuse in a metal clamp.

A safety feature is incorporated in the clock assembly of the bomb in the shape of a lever, which tends to prevent the mechanism from functioning while it is being loaded and handled.

This bomb is enclosed in a heavy transparent glass tube instead of a cast-iron shell. In loading the bomb, the necessary amount of explosive is put into a cardboard container which is placed in the bottom of the glass shell. After the clock has been wound, and the alarm set to go off in a certain number of hours, it is placed in the shell in such a manner that the blasting caps are embedded in the explosive. The ends of the glass shell are closed with metal caps and cork gaskets. The metal caps are tightened and held in position by a jam screw, operated through an endless metal band which is shaped to fit the shell. On account of the construction and light weight of this bomb it is necessary to enclose it in a short tin shell and weight it with sand before lowering on the shooting line.

The several advantages claimed for this type of glass shell may be summarized as follows:

1. Visibility and light construction. The mechanism of the bomb is in plain view at all times, and should it function prematurely, the vibration of the clock can be felt and the smoke from the burning fuse can be observed inside of the glass shell.

2. The glass shell is completely destroyed by the explosion, leaving no fragments to be drilled up and cleaned out.

Some failures of this bomb to explode are, no doubt, chargeable to defects or out-of-roundness in the glass shell, and to deterioration of the fuse at the exposed spot under the fulminate cap set in the metal base. The fuse is split to expose the powder core when clamped in the metal base, and as the device is not immediately used, the fuse is undoubtedly affected by atmospheric conditions.

Loading, Handling, and Placing Time Bombs

The time-bomb method of detonating torpedoes is comparatively recent. Since a number of lives have been lost in premature explosions of them, or where the bombs have been used, it is not unusual that these accidents should cause many persons to regard them as "infernal machines" or "shrapnel shells." The purpose of an explosive time bomb, like nitroglycerin, is to explode, although its destructive ability can usually be controlled by regard of the precautions required for the proper operation of this form of detonating mechanism. It is thought that the most frequent causes of premature explosion, in connection with the loading and handling of time bombs, may be summarized into three classes:

1. Possible hidden weakness or defect in the actuating unit or firing mechanism.

2. Carelessness in preparing and timing the bomb, or regulating it to explode too soon to permit it to be safely handled and lowered to the top of the torpedo in the well.

3. The unhooking of the bomb shell from the shooting line hook at some point in the well above the fluid level, thereby causing it to explode when it strikes the surface of the fluid.

It is estimated that an approximate combined total of 3200 electrical and mechanical time bombs have been used up to Jan 1, 1928, for detonating torpedoes in the Cromwell and Seminole fields, Oklahoma, and in the Amarillo field, Texas, with only three premature explosions involving loss of life. These disasters, referred to at the end of the paper, may be placed under one or more of the summarized causes outlined above. Obviously, the statement regarding the possible contributing conditions set out in summarized class No. 1 may be questioned, particularly since any evidence tending to substantiate it is destroyed in the explosion.

Although there has been considerable damage to wells, no attempt has been made to accumulate any data regarding it. Sometimes irreparable damage to wells has resulted from the detachment of time bombshells from shooting line hooks while lowering, thereby causing them to explode when they strike the fluid level. If an explosion does not take place, it may "go-devil" the torpedo and cause considerable damage, particularly if the operator has not had opportunity to bail or swab the water out of the casing. The author used a bailer to dislodge a time-bomb shell which had unhooked and landed on the shoulder of a reduced hole. The casing shoulder was saved, but as the result of a go-devil shot, the top of the bailer had to be jarred out of a bridge consisting mostly of sand line and iron from the lower part of the bailer.

Under no circumstances should a time-bomb shell be attached to, and lowered with, a torpedo shell containing nitroglycerin or any other

explosive. Aside from multiplying the hazard, such a practice furnishes the foundation for endless discussion as to whether the time bomb or loaded shell was responsible if a premature explosion occurs. Manufacturers of time bombs discourage the attachment to shells containing liquid nitroglycerin, but advocate the practice of placing them in the top of, or attaching them to, shells containing gelatinized explosives.

Regardless of the fact that gelatinized explosives are less sensitive than liquid nitroglycerin, it has been demonstrated in a tragic manner that those explosives are almost as destructive, in case of premature explosion from any cause, as if a shell loaded with liquid nitroglycerin had been used.

From some cause or other, some of these devices fail to function in the hole regardless of the care used in preparing them.

Occasionally "dead" bombs are accidentally fished out of the hole with equipment used to determine whether or not a torpedo has exploded, and it is reported that attempts have been made to take them apart. It is obvious that if the actuating unit in a time bomb became inactive, it may have stopped so close to the calculated time of explosion that handling or a slight jar might cause the firing mechanism to function.

Time bombs should be tested by the shooter, insofar as that can be done, before use. After the actuating unit has been timed by the shooter the torpedo companies usually require the representative of the operator to examine it to make sure the calculated time of explosion is correct.

The author has no desire to multiply or exaggerate the hazards of loading and handling time bombs, or to discourage their use. In the discussion of these hazards, the reference to specific types and instances has been purposely avoided.

This modern self-contained detonator, particularly desirable for use in deep wells, is economical and has many advantages over the various squibs. However, the successful use of time bombs, like the loaded squibs, requires intelligent handling by a capable and experienced oil-well shooter who is familiar with their construction and operation. Torpedo company employees load and handle time bombs and, unless specifically directed to do so by the operator, usually do not attach bombs to loaded torpedo shells.

Sand Firing Heads

This early form of detonation (sand firing heads) now obsolete in most fields, was designed to replace the dangerous firing head shells. The firing head shell was a regular 20-qt. shell having a small squib, similar to the present day line squib, built in the top of it. This squib was equipped with a firing tube which contained a two-piece plunger. Gun caps were fitted on the lower ends of the plunger and when the shell was filled the nitroglycerin extended up into the firing tube sufficiently to cover the gun

caps. This firing head shell, always the top one in a torpedo, was detonated by dropping a cast-iron go-devil down the hole.

To lessen the damage, should an accidental explosion occur, the firing head shells were replaced by the sand-firing head shell. This shell, made in the regular shell sizes, was constructed along the same lines and was detonated in the same manner as the squib end of the old firing head shells. The annular space between the firing tube and the walls of the shell was filled with sand. The sand-firing head shell is lowered in the same manner as any other loaded shell, although great care must be taken to see that it rests on top of the torpedo. The main objection to the go-devil is its uncertainty.

Jack Squibs

The jack squib is a tin tube about 2 inches in dia. and 3 to 7 ft. in length, and has a conical bottom. Ribs of the same metal of rectangular cross-sections are soldered along the outside of the tube to reenforce it. The conical bottom of the jack squib is equipped with a cast-iron tip which reenforces the end and prevents it from collapsing when it strikes the fluid.

The ordinary type of jack squib is made up by first filling up the conical end with fine sand and then loading the middle of the tin tube with one cartridge of 60 per cent. nitroglycerin dynamite, which has been primed with two blasting caps and sufficient lengths of waterproof fuse. The squib, with the two lengths of fuse extending a little above the top, is then packed full of dry fine sand.

Another form of jack squib, commonly known as the "Missouri Jack," is made up by loading the same type of tube with a 3/8-in. tin tube containing about 1/2 pt. of nitroglycerin. This glycerin tube and a blasting cap on the end of a fuse is packed in sand in the center of the squib. The desired length of fuse is wrapped around the glycerin tube and extends a little above the top of the squib.

Where ordinary jack squibs have a tendency to stop in upper caves, the so-called "Texas Jack" is employed. This type of squib is a combination of the ordinary jack squib and one joint of common anchor, the two being spliced together after the ordinary jack squib is made up. This type of jack squib is frequently desirable, in that it permits a longer fuse to be used than with the ordinary jack squib alone.

A jack squib for exploding a torpedo containing gelatinized explosive is made up in the same manner as an ordinary jack squib, with the exception that about 1/2 lb. of gelatinized explosive is used in addition to the one cartridge of dynamite.

A jack squib should not be dropped on shells of small diameter which have been anchored a considerable distance above bottom unless the shells have collars on them to stop the squib, otherwise a jack squib might

drop past them to bottom and destroy the anchorage without detonating the torpedo. As a rule jack squibs should not be used under a pressure greater than that of 1000 ft. of water.

The proper construction of jack squibs is a matter of great importance as a great deal of trouble can be, and has been traced to their improper construction and use. Sufficient fuse should be used to allow the jack squib to reach the bottom, as the abnormal increase in the burning rate of the fuse under hydrostatic pressure may cause the squib to explode in the casing. The normal burning rate for most waterproof fuse ranges from 32 to 40 sec. per ft., when burned above ground at sea level. Fuse should not be stored in any place where it will be subjected to comparatively high or low temperature. Extremes in temperature or damp storage, for any length of time, will retard the burning rate from 15 to 40 per cent. and may cause it to fail or burn irregularly.

In cutting a length of fuse for use in a squib, care should be taken to cut it square across. If a sharp knife is used it will not mash the fuse or leave a ragged end which would be difficult to properly insert in the barrel of the cap.

In inserting the fuse in the barrel of the cap, the end of the fuse should be placed against the explosive material contained in it before crimping the barrel to the fuse. Some shooters attempt to waterproof the crimped joint of cap and fuse by dipping it in some chemical preparation, although sometimes the compounds used for that purpose have contained liquid benzine derivativesor pyridene. Both of these substances are detrimental rather than helpful, as benzine or its derivatives have a destructive effect on the waterproofed exterior of the fuse, and pyridene tends to reduce the efficacy of mercury fulminate compounds.

Bumper Squibs

The bumper squib is a tin tube 2 inches in dia. and 5 ft. long, connected to a small shell. The shell portion is similar to a line squib and is equipped with a firing head.

The end of the wire line used for lowering the squib is passed through an eye in the bail and attached to a window weight inside the tube. A similar weight is attached to the bottom of the squib shell for the purpose of carrying it down.

A small amount of nitroglycerin is poured into the squib so as to cover the caps fitted on the firing head pins. After the squib has been carefully lowered to the top of the torpedo, sufficient slack in the wire line allows the upper window weight to drop and strike the firing head.

Any accidental impact against the firing head of a bumper squib while being lowered in the well would probably cause an immediate explosion. If it should lodge in the casing the explosion would undoubtedly rupture or sever the pipe.

Line Squibs

The line squib is a tin shell about 18 inches in length, and similar in construction and operation to the more or less obsolete sand firing head. This form of squib is employed to detonate torpedoes in wells where a jack squib hangs up or does not reach the shot.

The end of the wire line used for lowering the squib is passed through a hole in the firing head and attached to the bail of the shell. For the purpose of giving added weight to the shell, a window weight is attached to the bottom of it. When the squib has been lowered to the top of the torpedo the wire line should be drawn taut to take out all of the slack. A tubular cast-iron weight, reamed out at both ends is dropped over the wire line exploding the squib when it strikes the firing head. If the wire line is not taut the tubular weight may cut it when the weight strikes the top of the fluid in the well.

A modification of this squib, called the casing squib, is used for the purpose of severing "frozen" strings of casing or drill pipe. This type of squib is constructed by soldering the lower ends of several 10-in. lengths of stiff wire in equidistant positions around the lower end of a line squib.

When ready to lower the casing squib, the upper ends of the three wires are pulled far enough away from the squib to make the points of the wires drag along the casing while the squib is being lowered. When the proper depth in the casing has been reached, the squib is pulled up slowly until the points of the wire catch in the recess of the first collar. The squib is then detonated in the same manner as the ordinary line squib.

Electric Squibs

The electric squib is a small shell about 12 inches in length, in which a tube to contain nitroglycerin is soldered. The loaded squib tube is primed with an electric blasting cap or electric exploder, the cap and the bail of the squib being connected to a continuous length of duplex insulated copper wire. The annular space between the nitroglycerin tube and the outside wall of the shell is packed with fine sand, after which the squib is weighted on the lower end with a window weight and lowered with the insulated copper wire.

After the electric squib has been lowered to the top of the torpedo the casing may be pulled, carefully stripping each joint over the lead wire. The successful operation of this squib depends on the existence of an electrical circuit after it has been placed, therefore both the duplex insulated wire and the electric cap or exploder should be tested with a galvanometer before running them in the well with a loaded squib.

When the electric squib has been lowered to the top of the torpedo in the well, the insulated wire should again be tested for circuit with the galvanometer before the pulling of casing is commenced. This will enable

the shooter to pull the squib out and run another if the galvanometer shows the absence of a circuit, whereas if no test were made the torpedo would probably be buried when the casing was raised with the result that it would be impossible either to explode it or get sufficiently close to the top of it with another loaded squib. Further galvanometer tests should be made after the casing has been started so that the work of pulling casing may be stopped if the inrush of cavings from behind the casing has damaged the squib or the insulated wire. The squib is detonated by means of electrical current generated by a plunger-type battery. This means of detonation has attained wide use, particularly in wells where caving is expected after lifting the casing string. Its disadvantages are the high cost of the duplex insulated wire and the tendency of the wire to wad up and form a bridge in the open hole or casing when the torpedo is exploded.

If, for any reason, the circuit is broken during the pulling of the casing it is usually necessary to rerun the pipe to the casing seat and carefully clean out with drilling tools as close to the torpedo as possible without detonating it. This operation is dangerous as the explosion of the torpedo would, no doubt, damage the casing and warp or twist the tools so badly that they could not be removed from the well. If it is thought that the torpedo can not be detonated through the remaining cavings by the explosion of 10 qt. of nitroglycerin, the safest plan is to run a string of tubing and place an electric tubing squib through it.

The string of tubing is run with a wood plug in its lower end and usually the weight of the tubing will cause it to penetrate the cavings, although it may be necessary to rotate the string with tongs to get it to the desired point at, or near, the top of the torpedo. The wood plug is forced out of the tubing with water pressure and a small electric squib is lowered through the tubing with duplex insulated wire. The insulated wire should be tested for circuit with the galvanometer after which the tubing can be carefully stripped out over the lead wire and the casing again pulled out. There are available various types of pressure-proof cap containers which usually prevent collapse of electric caps or exploders from hydrostatic pressure in deep wells.

Spontaneous Explosion of Nitroglycerin Torpedoes in Oil Wells

The accidental discovery that nitroglycerin would explode spontaneously, when left in wells completed in the so-called "black lime" of the Ranger field, North Texas, resulted from the failure of an electric squib to detonate a torpedo which had been buried by cavings when the casing was raised.

Before the work of cleaning out the cavings on top of the torpedo could be started the charge exploded spontaneously. Since that time it has been the custom, in certain portions of the Ranger area, to place

torpedoes without detonators and permit them to explode spontaneously. The depths at which torpedoes have been placed and exploded spontaneously range from 3000 to 4500 ft. The elapsed time between the placing of the torpedoes in the wells and the spontaneous explosions has varied from 1 hr., 15 min. to 100 hr. Because some torpedoes explode spontaneously within 2 hr. when placed at depths of 3200 ft. and others within 100 hr. when placed at depths of 4200 ft., it would appear that the depth of the well is not necessarily a factor in connection with the time required to produce spontaneous explosion. The amount of fluid tamping on top of the torpedoes which exploded spontaneously has varied from 100 to 1600 ft. In wells where considerable tamping has been used it is thought that the hydrostatic pressure of the fluid column, in combination with other conditions later discussed, is a more or less important factor in bringing about decomposition and explosion.

According to determinations made by Van Orstrand of the U. S. Geological Survey, the average temperature of wells[15] completed in the black lime of the Ranger area was 131° F. at a depth of 3000 ft., with a geothermal gradient of 1° for each 47 ft. increase in depth.

Geologists state that the black lime of the Bend Series is interbedded with black carbonaceous shale, the two formations grading both vertically and laterally, one into the other from well to well. Microscopic examination of these sections of the black lime showed the presence of minute crystals of pyrite, although no data were obtainable whether the pyrite predominated in the black lime or carbonaceous shale.

Unusually high temperatures in shallow drill-holes penetrating pyritiferous beds in the Canal Zone were investigated in 1912 by MacDonald,[16] who concluded that the quick rise of temperature was due to the oxidation of finely divided particles of pyrite. Once oxidation of the pyrite had been started the heat generated tended to accelerate chemical action, thereby increasing the heating in geometric progression.

As a considerable head of either water or oil, or both, was standing in most of the Ranger wells in which spontaneous explosions occurred, it is probable that this condition tended to prevent oxidation.

Collom[17] made an investigation to determine the probable agency, or combinations of conditions, which caused nitroglycerin torpedoes to explode spontaneously in wells in North Texas fields. After reviewing the data just presented he summarized his suggestions and criticisms as to cause and effect as follows:

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[15] C. E. Van Orstrand: Work cited by R. E. Collom: Notes on Spontaneous Explosions of Nitroglycerin in Oil and Gas Wells, Stephens, Palo Pinto, and Young Counties, North Texas. U. S. Bureau of Mines, *Reports of Investigations* Serial No. 2119 (1920) 8 pp.

[16] D. MacDonald: Some Engineering Problems of the Panama Canal. U. S. Bureau of Mines *Bull.* 86 (1916).

[17] R. E. Collom: *Op. cit.*

1. In view of the fact that charges have exploded spontaneously both with and without detonators, this agency would seem to be removed as a possible factor of influence.

2. The nitroglycerin shells are open at the top; external and internal pressures are equalized, and therefore, consideration of the pressure factor is eliminated.

It is concluded that spontaneous explosions are the result of the continued reactions of unneutralized acids in the liquid, assisted by fairly high underground temperatures. Temperatures as already recorded may be sufficient to cause the explosive gradually to change chemically until detonation takes place. However, there may be an increase of temperature beyond that normally recorded, due to the oxidation of pyritiferous material, or to the reaction taking place between the unneutralized acid content of the nitroglycerin with the minerals, including oil and water, in the limestone and shale rocks.

According to Snelling and Storm:[18]

> Nitroglycerin begins to decompose at temperatures as low as 50° C. (122° F.) to 60° C. (140° F.). At a temperature of 70° C. (168° F.), nitroglycerin of commercial quality evolves enough nitrous fumes to give a decided test with potassium-iodide starch paper at the expiration of 15 to 30 minutes.

They found that nitroglycerin explodes at 218° C. (424.4° F.).

Nitroglycerin compounds can be exploded by ignition which is the probable method in the spontaneous explosions already discussed. However, nitroglycerin belongs to a group of explosives known as nitric esters which, in the words of Munroe and Hall[19]—

> are more effectively exploded by detonation through the use of an exploding device of mercury fulminate or the hydronitrid of a metal or by the explosion of a contiguous mass of the same ester.

By exploding with a detonator the molecules are literally "shaken apart," while in exploding by ignition the ordinary processes of oxidation ensue to a large extent, though the rate of combustion may so increase that detonation eventually takes place.

It is quite probable that in the spontaneous explosions, part of the nitroglycerin is wasted, prior to exploding, by decomposition and that the remainder is exploded through ignition in an incomplete manner.

Nitroglycerin, even when well made, is subject to decomposition at temperatures as low as 122° F. and, if the acid has not been completely removed, it is subject to decomposition at lower temperatures. There is danger, therefore, of an explosion in a well before the charge has been completely set, which may injure the well or cause loss of life. Also, there are possibilities of accidents, during the summer months, from poorly made nitroglycerin decomposing in the summer temperatures.

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[18] W. O. Snelling and C. G. Storm: Behavior of Nitroglycerin when Heated. U. S. Bureau of Mines *Tech. Paper* 12 (1912) 14 pp.

[19] C. E. Munroe and C. Hall: A Primer on Explosives for Metal Miners and Quarrymen. U. S. Bureau of Mines *Bull.* 80 (1915) 125 pp.

Thawing of Nitroglycerin, Gelatinized Explosives, or Dynamite

Liquid nitroglycerin is likely to freeze if exposed to continued temperatures of +10° to +13° C. (+50° to +55° F.) although in certain cases it has been known to remain fluid at much lower temperatures. These characteristics are to be expected, to a more or less extent, in most nitroglycerin explosives. The tendency of liquid nitroglycerin, or of other explosives of which it is an essential ingredient, to freeze is a source of danger in that oil-field stocks must be stored in heated magazines during the winter months.

As frozen explosives can be detonated only with difficulty, it is necessary that they be properly thawed before using if maximum efficiency is to be procured. To eliminate the objections arising from the tendency of nitroglycerin to freeze at comparatively high temperatures, admixtures have been used to lower the freezing point or to retard freezing by the formation of undercooled solutions. Such admixtures, which have been extensively used in some gelatinized explosives and nitroglycerin dynamites, which have attained wide use in the industrial field, include nitrated hydrocarbons or so-called nitro-substitution compounds, nitrated polyglycerins, and nitroglycol.

From a practical standpoint the use of certain admixtures in quantities sufficient to lower the freezing point of nitroglycerin to a satisfactory degree would be undesirable for the reason that the admixture would decrease the explosive energy and make detonation difficult.

Obviously, liquid nitroglycerin can only be used in oil-well torpedoes in the unfrozen state. Generally speaking, the torpedo companies have devoted little study to the matter of decreasing the sensitiveness or lowering of the freezing point of their product.

One large torpedo company has manufactured a low-freeze mixture thought to be a mixture of 25 per cent. nitrobenzol and 75 per cent. nitroglycerin. A considerable number of complaints were received from operators and shooters regarding the peculiar color and odor of the compound and the difficulty of detonating it in wells. Other torpedo companies have experimented at different times with relatively slight admixtures of glycol, and although the mixture also resisted freezing its use brought objections from shooters regarding its abnormal decrease in sensitiveness. No information is available regarding the handling of the admixture into the product, and it may be that improper technique was esponsible for the conditions complained of. It is also possible that some of the objections were the result of prejudice although it is inconceivable that an operator or shooter would knowingly discourage any improvement in the product the object of which is safety to life and property. With the manufacture of ethylene glycol on a large scale and its utilization as glycol dinitrate economically feasible as a satisfactory admixture to nitroglycerin, it is now possible for torpedo companies to

produce a less sensitive and low-freeze nitroglycerin without decreasing the explosive energy or impairing the stability of the mixture.

Rinkenbach[20] has devoted considerable time to the study of the properties of glycol dinitrate and in two papers reviews its growing consumption, freezing point, heat of combustion, hygroscopicity, and sensitivity to impact.

As many different kinds and grades of high and low-freeze explosives are utilized in the oil industry, field emergency methods of thawing will be discussed, although no attempt will be made to differentiate between explosives having different or lower freezing points and those which probably freeze at the usual temperature.

The thawing of frozen explosives requires time and extreme care. Improper methods have frequently resulted in serious and disastrous premature explosions, particularly with dynamite. It is dangerous to attempt to thaw a frozen explosive by placing it before a fire, near a boiler, on steam boxes or pipes, in extremely hot water, or in a bath of live steam.

Cans containing frozen liquid nitroglycerin may be safely thawed by first carefully pulling the corks and then suspending the containers in a barrel of warm water. The temperature of the water should not exceed 50° C. (122° F.) or be uncomfortable to the immersed hand. While nitroglycerin is comparatively insensible when completely frozen, it thaws slowly and is extremely sensitive during the thawing process. After the cans have been suspended in the barrel of warm water, any attempt to hurry the operation by putting additional hot water into the barrel is hazardous. Frozen gelatinized explosives, such as blasting gelatin (so-called solidified nitroglycerin), or gelatin dynamite (so-called torpedo gelatin) may be safely thawed by carefully putting the material in a grain bag and suspending the bag in a barrel of warm water. The temperature of the water should not exceed 50° C. (122° F.). After the gelatinized explosive has been thawed, the barrel should be removed from the locality and destroyed, because during thawing, nitroglycerin tends to separate from the other ingredients and sufficient exudation may settle to the bottom of the barrel later to cause an explosion.

The idea of filling a torpedo shell with frozen gelatinized explosive and then subjecting the shell to a bath of live steam is about as dangerous as the experiment of holding a bag containing frozen gelatinized explosive against a steam engine exhaust. Explosives subjected to such high temperatures are productive of quick and disastrous results.

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[20] W. H. Rinkenbach: Glycol Dinitrate in Dynamite Manufacture. *Chem. & Met. Eng.* (1927) **34,** 296; and Properties of Glycol Dinitrate. *Ind. & Eng. Chem.* (1926) **18,** 1195.

Nitroglycerin dynamite in small quantities may be safely thawed by placing the frozen cartridges in a water-jacketed tin container whose jacket is filled with water which has previously been heated to a temperature of not over 50° C. (122° F.). In no case should a vessel containing explosives, or one which has been used for thawing explosives be placed on or near a stove or fire.

In the work of thawing explosives it is of the utmost importance that no temperature in excess of 50° C. (122° F.) be employed.

While the theoretical or actual explosion points range from 160° C. (320° F.) for nitroglycerin to 200° C. (392° F.) for gelatinized explosives and nitroglycerin dynamites, it should be borne in mind that decomposition begins at a lesser temperature and the velocity of decomposition increases with a rise in the temperature employed. This is substantiated by the conclusions of Snelling and Storm already cited in the section on spontaneous explosions of nitroglycerin torpedoes in oil wells.

Results of Shooting Oil and Gas Wells

Oil Development and Extent of Shooting

A total of 721,621 wells were drilled and 9,441,546,000 bbl. of oil produced in the United States up to 1927.[21] Of that number of wells 29,319 were drilled during the year 1926. During the first half of the year 1927, 12,738 wells were drilled at a cost estimated at $245,362,000. Oil production was increased from 300,760,000 bbl. in 1916, to 770,874,000 bbl. in 1927, the latter figure representing 70.3 per cent. of the world's production during that year.

While it would be difficult, if not impossible, to estimate the probable extent of shooting or the benefits derived from it in the large number of wells drilled, it can not be doubted that the shooting of wells has been generally beneficial in the past and it has been largely responsible for the high oil production from many individual wells or fields.

However, it is possible that the benefits could have been increased by study and research with reference to the character, texture, porosity, and productivity of the formations penetrated; methods of shooting, size and spacing of torpedo shells, and the amount of explosive required to produce best results in individual wells.

Notwithstanding that producers generally have expended considerable time and money in efforts to increase the efficiency of other phases of operating and production practice, the problems of shooting have been more or less neglected. The attitude of many undividual operators on that point in the past may be partly chargeable to the thought that the monetary consideration paid to the torpedo company for the shot was as much a fee for properly shooting the well as for the explosive used,

[21] Petroleum—Facts and Figures. American Petroleum Institute, 1927, New York.

and in any event, the method of shooting and the size of the shot in wells on his own property had to be governed by how and to what extent his neighboring operator shot his wells.

However, during recent years, with the phenomenal growth of the petroleum industry and the multiplicity of operating difficulties in wells of great depth, the need of study and detailed information regarding drilling and operating problems has been realized. As a result most large producing companies have established engineering organizations which have included the problems of shooting within their activities.

Suggested Data on Sampling, Logging, Production, Etc.

Often it has been impossible to determine, with any degree of accuracy, the results or benefits derived from shooting individual wells because records and other essential data have been inadequate and incomplete. The meager records of many such shots frequently consist of: "Well shot Oct. 1, 1927, 60 qt., 4100–4130. Initial production 100 bbl."

Such data are merely a record that a certain quantity of nitroglycerin was exploded on that particular date between the depths mentioned. Nothing is recorded concerning the production of gas, oil, or water; or of methods of production, fluid levels, and the condition of the well before and after shooting. If such a record is to be complete and in sufficient detail it should be commenced at the top of the productive horizon.

As the rotary system of drilling is seldom employed to complete wells in the sand in areas where shooting is generally carried on, it is generally a comparatively simple matter to obtain information with the standard or cable-tool method of drilling. Whenever possible the zone where production is expected should be drilled or cored in short stages so that the cuttings or cores may be carefully examined for the purpose of defining and recording the character, porosity, productivity, and thickness of the formations penetrated. Provided that the hole is thoroughly bailed after each screw, it will be possible to obtain more or less uncontaminated samples which should enable the engineer or driller accurately to log the footage of barren streaks, hard medium or soft pay, and shale breaks.

As a rule, more accurate and complete information with reference to sand conditions and the porosity of productive strata can be obtained from cores taken with a double-tube, cable-tool core barrel. Such core barrels have been successfully operated at depths in excess of 6000 ft., yet as they have no watercourses and are constructed so that a full gage hole can be drilled, it is obvious that they can not be lowered in the hole against a large oil or gas flow. While the data and information obtained from core samples are important from the standpoint of the shooting and production problem they no doubt will be equally valuable if case-

repressuring operations are to be considered during the later life of the well or lease.

If the well does not produce naturally after the total depth has been reached, it should be bailed to remove water, "frog," or shale mud from the hole. The fluid levels should be accurately measured before and after shooting and in order to determine the flow of fluid into the well it is advisable to make corresponding production tests by pumping, bailing, or swabbing. In case the well produces naturally after the shot the production should be carefully gaged in tankage set apart for that purpose.

Frequently, the uncertainty resulting from undue haste, or the inability or failure to obtain and interpret samples or cores at short intervals while drilling in, has often led to the erroneous impression that the entire footage between the first show of oil and the total depth of the hole was more or less productive. This has probably caused many operators to spend money needlessly later for nitroglycerin in shooting uniformly throughout the entire section of formations, whereas a lesser charge could probably have been spaced and distributed more advantageously.

As crooked holes undoubtedly contribute to the difficulties and dangers of lowering nitroglycerin torpedoes and of subsequent production operations, a careful record should be made while drilling-in as to any wear on the line or tools which might indicate deviation of the hole from the vertical. With the increased depth of wells and speed of competitive drilling, particularly with the present rotary tools and method, it is mechanically impossible to drill a vertical hole to any considerable depth. This trend toward deviation is increased in rotary-drilled wells where it has been necessary to sidetrack drill-pipe or tools. Interesting data regarding deviation are shown by the survey of a number of rotary-drilled wells in California, made by the Anderson method, which show the average deflection from the vertical to be 159.9 ft. at depths of 3000 ft., 261.7 ft. at depths of 4000 ft., and 421.6 ft. at depths of 5000 feet.

While the geologic section in Californian fields is unlike that of the Mid-Continent area, it remains a fact, that although not surveyed, certain rotary-drilled wells in the Seminole field have shown as much deflection from the vertical. This is illustrated by several wells, 660 ft. apart on the surface, which intersected at drilling depths around 3000 feet.

Practice and Results in Mid-Continent Fields

As sand conditions vary within wide limits from well to well and from one area to another, it is plain that any discussion of methods or amounts of explosive required to produce best results would necessarily have to be based on assumed conditions which probably would not obtain in actual practice.

Considering that the diversity of opinion among operators on the question referred to is almost as wide as the diversity in sand conditions, it is thought that further study of the problem can better be stimulated by the presentation of data showing the methods of shooting and results obtained from various quantities of explosive in some of the Mid-Continent fields.

In studying the shooting problem it should be remembered that a torpedo equal in length to the thickness of the formations shot will extend its sphere of work above and below the ends of the charge. This is illustrated by the destruction or shattering of casing seats, the shattering and caving of overlying shales or less resistant formation, and by breaking into bottom water when shots are exploded too close to them.

Where it is desired to shoot one or more sections of the formations, it would be good practice to use a torpedo of such length that it will extend several feet below the top and an equal distance above the bottom of the formations to be shot. Increased brisance or descriptive effect can usually be obtained by increasing the diameter of the shells used in a part or all of the torpedo.

Unless the casing or liner has been landed far enough up the hole or can later be lifted, the extent of tamping and the maximum size of the charge is regulated by the distance between the bottom of the last string of casing or liner and the top of the shot, because it is necessary that the top of the water-tamping be kept well below the bottom of the casing or liner.

The almost instantaneous nature of the reaction only requires that a relatively short column of fluid tamping be placed on top of the torpedo to prevent dissipation up the hole of the energy of explosion. However, the tamping necessary to accomplish that end is more or less proportional, within certain limits, to the amount of explosive used. Table 3 affords a quantitative idea of the tamping and explosive used in wells where the distance between the bottom of the casing or liner and the top of the shot is less than 100 feet.

TABLE 3—*Distance from Casing Shoe to Top of Shot, Extent of Tamping, and Size of Shots in Mid-Continent.*

Distance from Casing Shoe to Top of Shot, Ft.	Tamping (Water) on Top of Shot, Ft.	Size of First Shot (Nitroglycerin), Qt.	Size of Second Shot (Nitroglycerin) Qt.
30	20	10	20
50	40	20	40
70	50	40	
80	60	60	
90	70	80	
100	75	100	

The data in Table 3 are thought to be close enough to the danger point, although several instances have been reported where torpedoes have been exploded at lesser distances from the casing without damage to it. Where light shooting is done at sufficient distances below the casing or liner in wells flowing steadily or by heads the live oil tamping may safely extend up into the casing or liner a short distance without much danger of rupturing it.

Seminole Field

In the Seminole, Oklahoma, field, production comes from the Hunton limestone, Simpson dolomite, upper Wilcox sand, and the lower Wilcox or so-called Gypsy sand. From the standpoint of shooting, the conditions were ideal in wells drilled to the Simpson dolomite or Wilcox sands because the last string of casing was usually landed in the top of the Viola limestone, 50 to 100 ft. above the productive sand. The same factor of safety did not attend the shooting of wells completed in the Hunton limestone because it was necessary to land casing at the top of that formation, and the oil pay was found at comparatively shallow depths below the top of the sand body.

In most upper Wilcox sand wells the oil production was apparently regulated by porosity and structural position, although where sand conditions were favorable a number of wells in structural depressions obtained comparatively high initial production. In the more resistant Hunton and Simpson limestone beds, porosity was largely dependent on the degree of gradation from lime to sandy lime or sand.

The Hunton limestone is hard, white, and crystalline, and where present, ranges in thickness from a thin shell to around 80 ft. In some parts of the field this formation grades into a sandy lime, and in structurally high wells the principal oil production is found in a porous sandy member 30 to 40 ft. below the top of the bed.

The Simpson dolomite is a series of hard dolomitic limestones, 30 to 50 ft. in thickness and lying between the base of the Viola limestone and the top of the upper Wilcox sand. In some wells oil production is found in the sandy lower portion of the dolomite.

The upper Wilcox sand is a section of more or less loosely cemented white quartz sand about 150 ft. in thickness lying immediately below the Simpson dolomite and above the Wilcox dolomite. The sand body contains shale breaks, varying from a few inches to several feet in thickness, although this condition seems to be of local occurrence and not uniform over the field; notwithstanding the considerable thickness of the upper Wilcox section, oil production comes only from its upper portion.

The lower Wilcox, or so-called Gypsy, is a white quartz sand found about 50 ft. below the base of the upper Wilcox sand, and is separated from it by the so-called Wilcox dolomite. Only a comparatively few

wells in the Seminole field have obtained production from the lower Wilcox sand as in a majority of wells it has either been barren or productive of water.

As most of the upper Wilcox sand wells began to flow naturally, it was not necessary to shoot for the purpose of obtaining a maximum initial production. During the earlier development of the Seminole field considerable light shooting was done to stimulate the production and natural flow of wells that had either ceased to flow or developed a reduced periodic flow.

Frequently, the 10 or 20-qt. shots served to induce natural or increased flow, the result being that a number of individual wells were shot two and three times. Where natural flow could not be reestablished by shooting and swabbing, the wells were placed on the air-gas lift. The latter condition was more or less characteristic of wells completed during the later development of the field, or wells in which shooting had been delayed due to orders issued by the Corporation Commission of Oklahoma restricting shooting during the proration and curtailment programs of 1927 and 1928.

In considering the methods and results of shooting in the Seminole field we are confronted with conditions which often make it difficult to estimate the benefit derived therefrom. While accurate data on shooting and individual well production have been kept, the results of shooting are obscured to a certain extent by variation in production methods and operating conditions before and after shooting. This is particularly true of the many wells which were formerly produced by natural flow or swabbed for production during the periods of proration and restriction and which were put on the air-gas lift immediately after they had been shot, cleaned out, and swabbed for a relatively short time.

Following the shooting, a number of the short swabbing tests either showed the result to be negative or that only a slight increase in oil and gas production or fluid levels had been obtained. The resultant high oil production induced by the later air-gas lift operations indicates that relatively short swabbing tests are not always conclusive. As a rule, the amount of oil that can be procured from individual wells by intermittent swabbing is limited, especially in wells where enough formational gas is not produced to assist the operation mechanically.

The upper Wilcox sand ranged from medium to soft in point of hardness and the quantity of nitroglycerin used in individual torpedoes varied from 5 to 40 qt. Where solidified nitroglycerin or torpedo gelatin was employed, the amount used was the assumed equivalent of a certain amount of liquid nitroglycerin although, because of composition and lack of density in the explosive within the torpedo shell it probably was much less. The data covering 205 liquid nitroglycerin torpedoes placed in upper Wilcox sand wells shows the average amount of explosive

used to be 23.8 qt. or 1.4 qt. per linear foot of formation opposite the torpedo.

As a rule, where shooting had not been delayed too long the first, and sometimes the second shots in individual wells were beneficial although little or no benefit resulted from subsequent shooting. Table 4 gives data regarding a number of Seminole wells and shows depth below sea level to top of the upper Wilcox sand, total depth, initial daily production, duration of natural flow and daily production before and after shooting. The letters designating the number of the individual wells named in the table correspond to the letters appearing on the production curves (Figures 1 to 9) presented in the later discussion of these wells. Although all of these wells were completed during the early development of the field, it will be noted that shooting was not always accomplished until after the wells had been produced by various methods for periods ranging from one to six months.

Discussion of Individual Wells

Well *A* is the only one included in Table 4 which is producing from both the upper and lower Wilcox sands and never has been shot. The production secured by the air-gas lift from this structurally high well, during the period May, 1927, August, 1928, is shown by Fig. 1. While the curve shows a satisfactory rate of production and decline without shooting, it can not be used for the purpose of comparsion with the rate of production and decline of wells completed in the upper Wilcox sand only.

Well *B*, one location south of well *A*, was completed on the same date in the upper Wilcox sand in May, 1927, with an initial daily production of 500 bbl., by swabbing. After a 20-qt. shot of nitroglycerin the production was increased to 3000 bbl. as shown by Fig. 2, the operating method being the air-gas lift. It may be noted that the rate of decline in the oil production of well *A* was rapid during May and June, 1927, but that the curve was flattened when it reached the point of well *B*'s production in July, 1927. Further evidence that these wells bear a certain relation to each other is furnished by the fact that shooting only increased the production of well *B* to the then daily production of well *C* which had been completed several months before and shot on May 1, 1927.

Well *C* was completed in the upper Wilcox sand during March, 1927, with an initial production of 6400 bbl. by natural flow. The well ceased to flow on April 25, 1927, but after shooting 20 qt. of nitroglycerin, the daily production was 3500 bbl. by air-gas lift as shown by Fig. 3.

The upper Wilcox sand in this well was extremely soft and shooting caused considerable caving. However, the additional time required to clean out the hole thoroughly was probably well spent, as no doubt the increased drainage from the exposed face of the sand in the shot-hole has

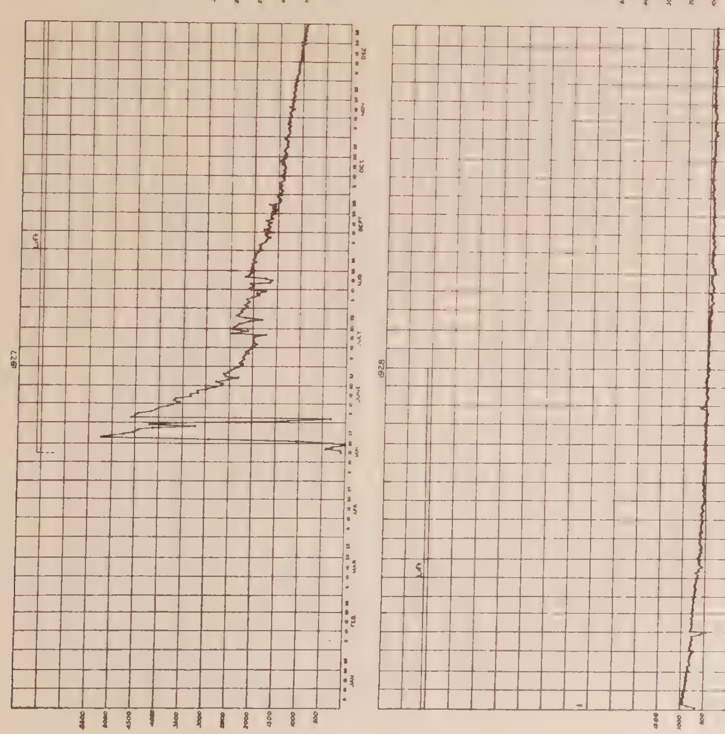


Fig. 1.—Daily production of well *A*, May, 1927, to January, 1929.

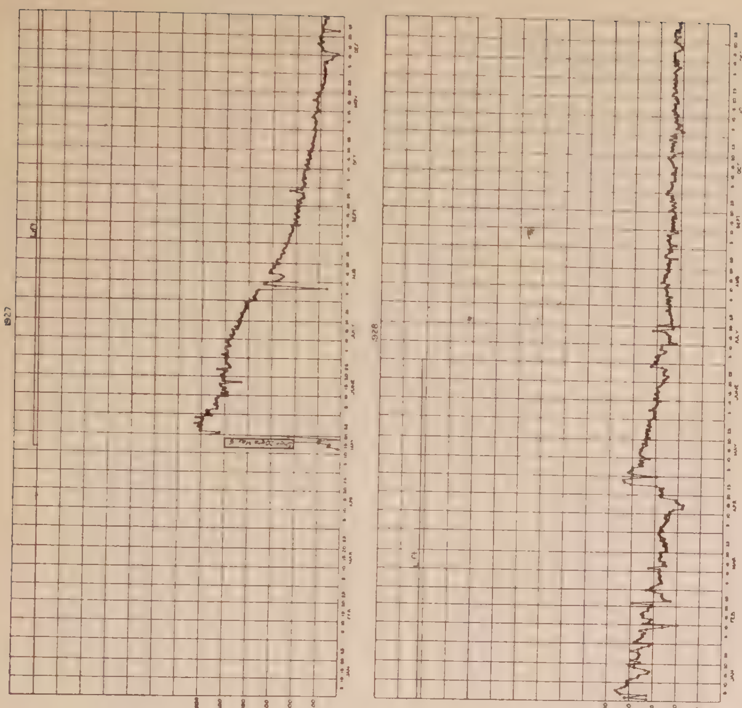


Fig. 2.—Daily production of well *B*, May, 1927, to January, 1929.

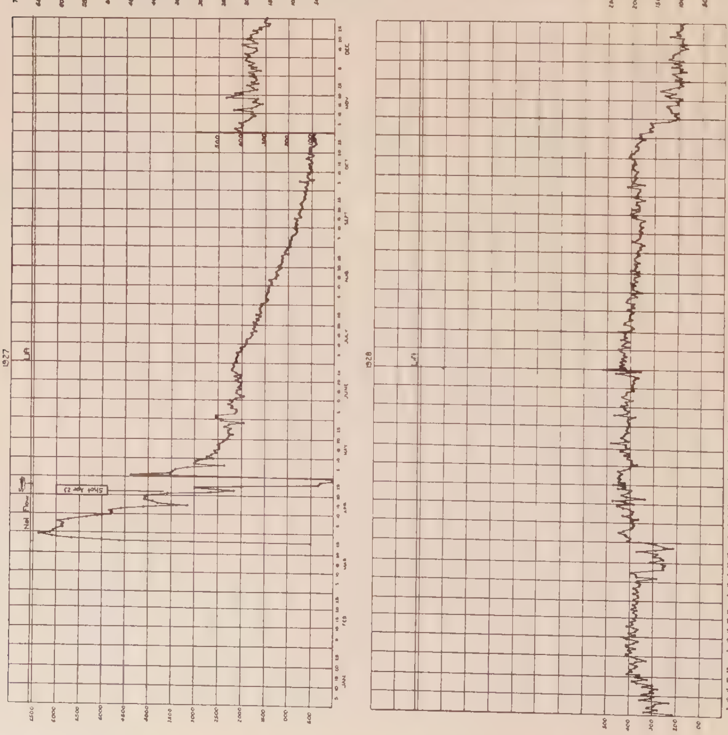


FIG. 3.—DAILY PRODUCTION OF WELL *C*, MARCH, 1927, TO JANUARY, 1929.

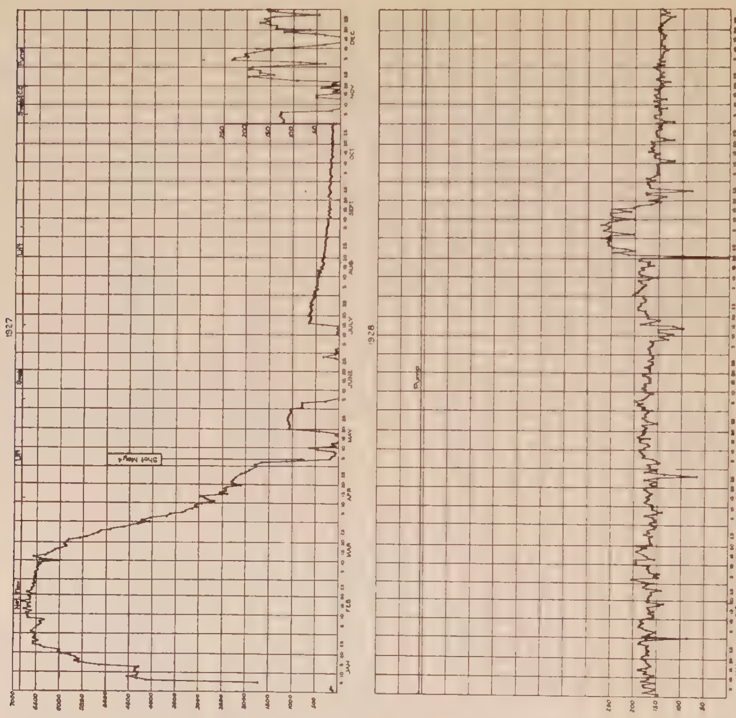


FIG. 4.—DAILY PRODUCTION OF WELL *D*, JANUARY, 1927, TO JANUARY, 1929.

contributed largely to the comparatively high daily oil production during the later life of the well.

Well *D* was completed in the upper Wilcox sand in January, 1927, and during the following three months produced 592,378 bbl. of oil by natural flow as shown by Fig. 4. The well was shot with 20 qt. of nitroglycerin on May 3, 1927, but no increase was secured from this or the subsequent shot placed in the upper Wilcox sand July 14, 1927. This and other similar results seem to show that previous drainage through the well itself, and the influence of nearby wells, are factors to be considered in connection with the shooting of wells of this type.

Well *E* was completed in the upper Wilcox sand in June, 1927, with an initial daily production of 500 bbl. by swabbing. It was placed on the air-gas lift, increasing the production to 1500 bbl. daily. This well was structurally low, the top of the upper Wilcox sand being 100 ft. lower than in the West offset well *F*, and 105 ft. lower than in the southwest diagonal offset well *H*. After well *E* had been produced by the air-gas lift for six months, it was shot with 10 qt. of nitroglycerin although, as shown in Fig. 5, the oil production was not favorably affected.

Well *F* was completed with a penetration of 3½ ft. in the upper Wilcox sand on April 15, 1927, at a total depth of 3264½ ft. below sea level. The well was produced by natural flow for a period of 30 days, during which period the production declined from the peak of 7540 to 3750 bbl. daily. After the well had been placed on the air-gas lift May 15, 1927, the oil production was increased to 5000 bbl. daily, that being 1250 bbl. higher than the last daily production by natural flow. When the production by air-gas lift had declined to 700 bbl. daily on Oct. 13, 1927, some cavings were cleaned out and the well was shot with 20 qt. of nitroglycerin.

The usual shot-production test was made by swabbing after the shot and the result seemed to indicate that no increase had been obtained, although after air-gas lift equipment had been reinstalled it was found that the oil production had been increased from 700 to 2500 bbl. daily. The fluctuations in the daily production of this well are shown in Fig. 6. This is one of perhaps many instances where the benefits resulting from shooting can be approximated, because the conditions under which the air-gas lift was operated were the same after as they were before shooting.

Assuming that the production curve would flatten out at 700 bbl. without shooting and that it would not fall below that figure from Oct. 13, 1927, to April 30, 1928, we find that the amount of oil produced in excess of 700 bbl. daily during that period was 100,085 bbl. This large increase, undoubtedly due to shooting, is unusual in that the well had produced over 450,000 bbl. of oil to that time.

Well *G* was completed in the upper Wilcox sand during the latter part of 1926, in the older north portion of the field, and had an initial daily production of 10,000 bbl. After having produced a total of approximate-

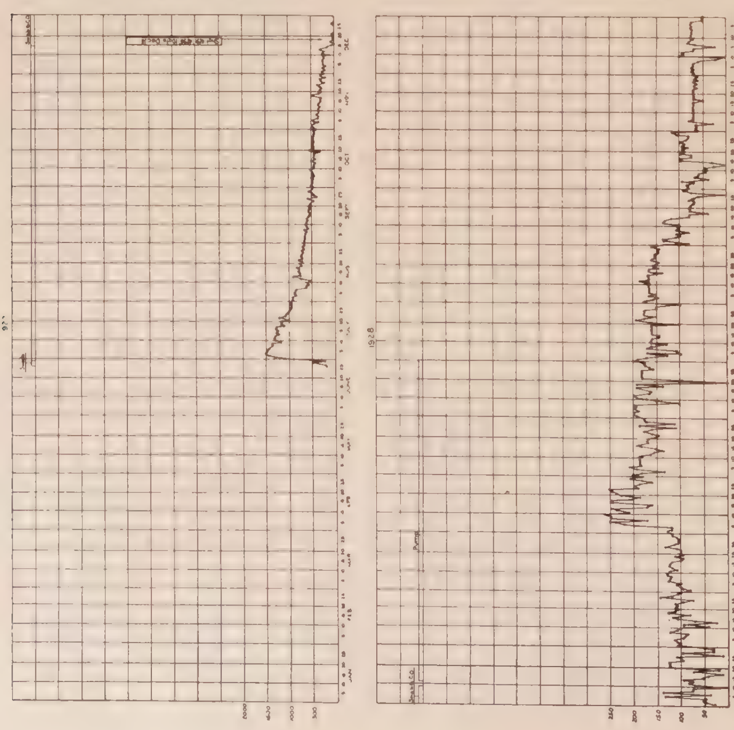


FIG. 5.—DAILY PRODUCTION OF WELL *E*, JUNE, 1927, TO JANUARY, 1929.

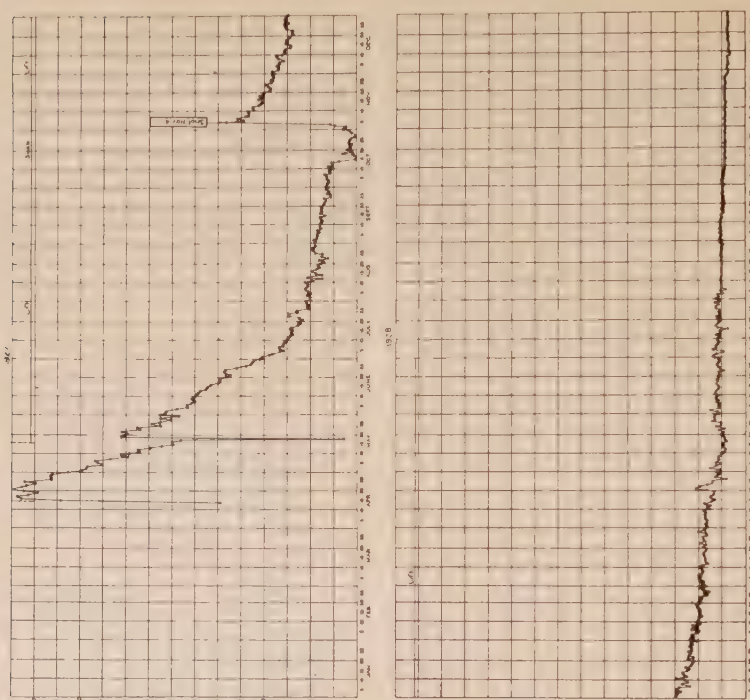


FIG. 6.—DAILY PRODUCTION OF WELL *F*, APRIL, 1927, TO JANUARY, 1929.

TABLE 4.—*Oil-well Data, Seminole Field, Oklahoma*

Well No.	Elevation (above Sea), Ft.	Date Completed	Top Upper Wilcox Sand (below Sea), Ft.	Character of Sand (Hardness)	Total Depth (below Sea), Ft.	Initial Daily Production, Bbl.	Duration of Natural Flow	Accumulated Production before Shooting, Bbl.	Daily Production before Shooting, Bbl.	Record of Shooting: Date	Record of Shooting: Qt.	Record of Shooting: Size Shell Inside Dia., In.	Record of Shooting: Depth of Shot, Ft.	Production after Shooting: Water	Production after Shooting: Oil	Accumulated Production, Aug. 1, 1928, Bbl.
A	884	May, 1927	3,048	Medium[f] Soft[f]	3,127[a]	5,200[f]	May 20 to May 25									557,896
B	918	May, 1927	3,198	Medium	3,232	500[b]		None	500[b]	5/14/27	20	2[c]	4,116 to 4,147	None	3,000[c]	376,391
C	918	March, 1927	3,190	Soft	3,200	6,400	Mar. 25 to Apr. 25	142,671	250[b]	4/22/27	20	2½[e]	4,108 to 4,128	None	3,500[c]	527,262
D	920	January, 1927	3,126	Medium	3,158	6,700	Jan. 5 to Apr. 10	592,378	1,700[c]	5/3/27	20	2[c]	4,047 to 4,078	None	1,000[c]	688,957
E	926	June, 1927	3,366	Medium	3,375	1,500[c]		105,000	250[c]	12/18/27	10	3½[e]	4,291 to 4,296	None	150[d]	136,154
F	965	April, 1927	3,261	Soft	3,264½	7,540	Apr. 15 to May 17	456,513	700[c]	11/4/27	20	4½[e]	4,216 to 4,222½	None	2,500[c]	733,902
G	852	October, 1926	3,191	Medium	3,208	10,000	Oct. 25 to Dec. 10	630,000	1,200[c]	8/7/27	15	3 4[e]	4,040 to 4,060	None	2,000[c]	871,742
H	933	January, 1927	3,261	Medium	3,267	5,500	Jan. 1 to Apr. 23	446,747	250[b]	7/8/27	10	2[c]	4,201 to 4,217	None	1,000[c]	556,870

[a] Upper Wilcox thinned and well completed in Lower Wilcox sand.
[b] Swabbed.
[c] Air-gas lift.
[d] Pumped.
[e] Water-jacketed; outside diameter measurement is ½ in. larger than inside diameter.
[f] Production from upper and lower Wilcox sands.

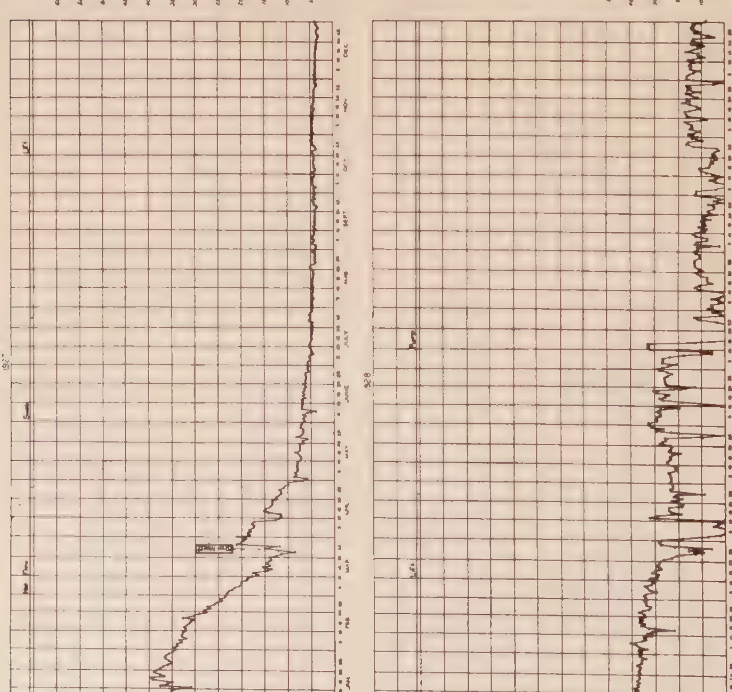


FIG. 7.—DAILY PRODUCTION ON WELL *G*, JANUARY, 1927, TO JANUARY, 1929.

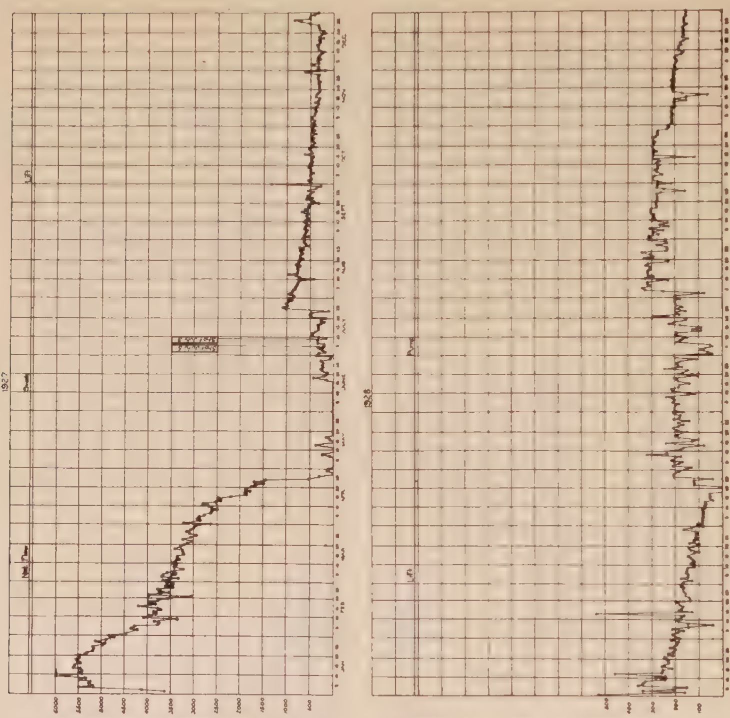


FIG. 8.—DAILY PRODUCTION OF WELL *H*, JANUARY, 1927, TO JANUARY, 1929.

ly 650,000 bbl. by natural flow and the air-gas lift, the well was shot with 15 qt. of nitroglycerin on March 26, 1927. The oil production was increased from 1350 bbl. to 2000 bbl. daily, the former being by air-gas lift and the latter by natural flow. An estimate of the beneficial results obtained by shooting in this well, as shown in Fig. 7, is 15,000 bbl.

Well *H* was one of the early completions in the east portion of the field, being completed in the upper Wilcox sand during January, 1927, with aninitial daily production of 5500 bbl. by natural flow. After having produced 400,000 bbl. from a penetration of 6 ft. in the upper Wilcox sand, the well started to produce a small amount of salt water and then it ceased flowing. In deepening the well from 3267 to 3357 ft. below sea level an additional amount of water was found, and the hole was plugged back to 3327 ft. below sea level. The sand was then shot with 20-qt. torpedoes in 10-ft. stages, the well being swabbed to test production after each shot. As may be noted in Fig. 8, little or no benefit was derived from shooting.

The methods employed in placing nitroglycerin torpedoes in wells of the Seminole area were not unlike those employed in other fields, although sometimes it was necessary to install special equipment in the form of a lubricator so that the loaded shells could be lowered against the restricted natural flow of the well.

In wells that did not produce by natural flow, the rising column of live oil usually extended up into the casing despite the efforts made to keep it swabbed down and was used as tamping for the shot. As the great depth of wells made it extremely dangerous to attempt the use of anyone of the various modifications of the squib, detonation was accomplished with time bombs.

Conclusion Regarding Value of Shooting Wells

An analysis of the results obtained from shooting, particularly in the upper Wilcox sand, leads to the conclusion that moderation in shooting the more or less soft sand and the subsequent use of the air-gas lift, have been largely responsible for the large increases in oil production. These results have appeared outstanding for the reason that these unusual increases probably could not have been brought to the surface by any other method of production except possibly by natural flow.

Papoose Field

In the Papoose, Oklahoma, field, production comes from the Papoose sand which has been correlated with the Cromwell sand of the Cromwell field (Oklahoma) and with the Lyons-Quinn sand of the Lyons-Quinn field (Oklahoma). The sand body ranges from 60 to 80 ft. in thickness,

although in some wells 1 to 20 ft. of the upper portion is a barren cap rock of lime or sandy lime and shale.

As a rule, casing was landed immediately above the Papoose sand zone, although sometimes the casing was landed below the overlying Gilcrease sand with a liner extending to the top of the Papoose sand. In either case shooting under certain conditions, or with more than a light charge, was hazardous because production was found at comparatively shallow depths in the sand and it was difficult, if not impossible, to lift the casing or liner for the purpose of shooting.

The oil-productive portion of the Papoose sand varied from medium to soft in point of hardness and the amount of nitroglycerin used in individual torpedoes varied from 2 to 10 qt. In considering the results obtained from shooting in this more or less loosely cemented sand, we find another instance of where moderation in shooting enforced by necessity as well as judgement, has produced unusual increases in production.

TABLE 5.—*Oil-well Data, Papoose Field, Oklahoma*

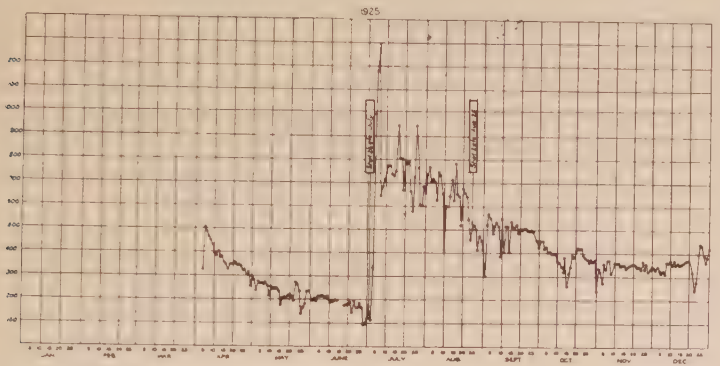
Item	Well					
	I	*J*	*K*	*L*	*M*	*N*
Elevation, ft.	888	877	780	802	785	802
Date completed, 1925	May	April	March	March	March	January
Hardness of sand	Soft	Soft	Medium	Medium	Soft	Medium
Top of sand below sea, ft	2500	2500	2522	2514	2502	2487
Total depth below sea, ft.	2519	2524	2533	2531	2530	2511
Daily initial production, bbl.	1050[a]	500[a]	1580[a]	1283[a]	1290[a]	2250
Daily production before shooting:						
Oil, bbl.	400[b]	175[b]	400[b]	460[b]	345[b]	265[b]
Water	Trace	None	None	Some	None	None
Shooting record:						
Date, 1925	July 5	July 3	May 14	May 16	April 10	June 24
Amount, qt.	2½	2½	5	5	5	10
Size of shell, in.	2½	2½	2½	2	1¾	2½
Depth of shot, ft.	3402–3405	3396–3399	3316–3321	3325–3332	3303–3313	3302–3309
Daily production after shooting:						
Oil, bbl.	830[a]	1300[a]	438[b]	None[c]	1015[a]	210
Water	Trace	None	None	None	None	None

[a] Natural flow.

[b] Swabbed and flowed; swab operated once an hour.

[c] Pipe split by shooting.

As a rule, the first and second shots were beneficial although, as in the Cromwell and Seminole fields, little or no benefit was derived from late or subsequent shooting. Data regarding several representative Papoose field wells, showing the depth below sea level to the top of the Papoose sand, total depth, initial production and daily production before and after shooting are in Table 5. The letters designating the individual wells correspond to the letters appearing on the production curves presented in the later discussion of these wells.



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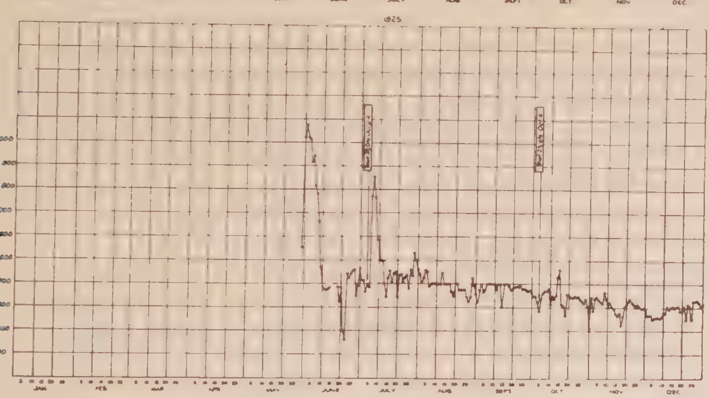

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FIG. 9.—DAILY PRODUCTION OF WELL *I*, MAY, 1925, TO JANUARY, 1926.
FIG. 10.—DAILY PRODUCTION OF WELL *J*, APRIL, 1925, TO JANUARY, 1926.

The production of well *I*, as shown by Fig. 9 represents an unusual benefit from shooting with a small charge. An estimate of the amount of production to Dec. 31, 1925, above the level to which the well had declined in June, 1925, is 7500 bbl. Extending this estimate until the well had again declined to its former level of 150 bbl. during the year 1926, we have an excess of 100,000 bbl. which must be credited to shooting.

Fig. 10 shows that the production of well *J* was benefited by shooting through a temporary increase, but the major beneficial result came from

a sustained production extending over the following 8 months and into the year 1927.

It is doubtful whether any nitroglycerin in excess of the amount generally used would have accomplished the same or an increased result. The use of larger torpedoes in several wells has resulted in reducing the oil production or damaging the casing, or both.

Panhandle Fields, Texas

Where oil production is obtained from hard lime formations, as in parts of the Borger and Pampa areas, it has been customary to shoot with 200 to 1,000 qt. of nitroglycerin, or the theoretical equivalent in gelatinized explosives. In wells where the shots were larger and too close to the bottom of the casing it was necessary to lift the pipe after the torpedo and time bomb had been placed. In several other wells

TABLE 6.—*Production Data for Several Wells in the Panhandle Field (Borger, Texas) before and after Shooting*

Item	Well					
	O	*P*	*Q*	*R*	*S*	*T*
Date completed	April 16, 1926	April 1, 1926	April 6, 1926	Nov. 10, 1925	Feb. 1, 1925	July 4, 1926
Depth of limestone, ft.[a]	2820–3035	2830–3080	2851–3010	2740–2850	2962–3065	2764–2910
Production before shooting, bbl.	300	60[b]	55[c]	100[c]	52[d]	
Shooting record:						
Date	April 20, 1926	April 12, 1926	April 10, 1926	Nov. 25, 1925	Sept. 1, 1925	Aug. 5, 1926
Amount, qt.	650	990	505	210	240	210
Size of shell, in.	5½	6½	6½	4	5	4¾
Depth of shot, ft.	2895–3020[e]	2905–3076[e]	2910–2995	2765–2841	2992–3056	2840–2901
Production after shooting:						
Oil, bbl.[c]	4500	5000	5480	1000	175	300
Water	None	None	None	None	None	None

[a] Casing is usually landed on top of lime.

[b] Swabbed.

[c] Natural flow.

[d] Pumped.

[e] Bridged on top of shot and hole filled to point close to casing shoe with river gravel, clay, and oakum. Casing is then filled with oil.

where the tops of large torpedoes extended to within 75 ft. of the casing shoe, the hole above the charge was filled up 70 ft. with river gravel, clay and oakum, after which the casing was filled with oil. While this method of shooting resulted in a satisfactory increase in production and apparently did not damage the casing, it has not been used in enough wells to form any conclusion as to its efficacy under all conditions.

Table 6 gives data regarding several Panhandle wells and showing the oil production before and after shooting. A study of this tabulation will reveal that shooting, particularly during the early life of wells, has been a profitable practice from the standpoint of developing Panhandle production.

The failure of certain lime wells to respond to heavy shooting is probably chargeable to formation or structural conditions or to shooting in muddy holes. It has been found that oil strata containing granite wash, shale, or anhydrous formations ordinarily do not react favorably to heavy shooting, particularly where water is present. It is probable that more damage has been done in Panhandle wells by shooting in muddy holes than from any other single cause.

The amounts of nitroglycerin used in individual wells, no doubt, are excessive and many times not actually required to shoot into the richer accumulations at some particular point in the well. However, as the Panhandle limes are often barren or contain such uncertain indications when first drilled, the operator generally desires to shoot a considerable portion of the entire section as heavily as he can even though the operation may involve more expense than otherwise might have been necessary.

Poteau, Oklahoma, Gas Field

This more or less depleted gas field, the Poteau, is added to this discussion because it appears to have been the only gas-producing area in the Mid-Continent where shooting has been done to any extent in connection with natural gas production. In addition, this field presents a mass of interesting data because the results were obtained through unusual methods and materials. Gas production from wells is obtained from a hard, close-grained section of the Hartshorne sandstone. The holes do not curve and only 100 or 200 ft. of casing is required.

The gelatin or dynamite explosive was loaded in shells made up by the local tinsmith, the work of loading and lowering the shells being done by company employees. Where gelatin was used as the major explosive charge, a number of pieces of 60 per cent. nitroglycerin dynamite was spaced through each shell to aid in detonation. Table 7 gives data regarding a number of wells drilled in the Poteau gas field showing the gas volumes before and after shooting.

While the data show that beneficial results may be expected from shooting in this type of gas sand, we have no comparative values and therefore no basis for any conclusion that the maximum obtainable benefit has been obtained by the use of these methods and materials.

In connection with the application of either explosive gelatin or gelatin dynamite in oil-well torpedoes, the individual characteristics and relative insensibility of these explosives present a number of difficulties which must be overcome if effective detonation is to be procured. Otherwise, the explosive process may assume the character of a deflagration rather than a detonation, and it is possible that a portion of the charge may neither be burned nor exploded. Instances are reported from Kansas where pieces of unexploded gelatin have been ejected from the well, and one case where the unexploded portion of a shot was drilled up and later bailed out.

It is possible that the ordinary methods of detonation might be greatly assisted by stringing a line of Cordeau from the top to the bottom of each shell in the center of the charge. Cordeau consists of a lead tube 0.23 in. in dia. filled with trinitrotoluene (T N T). It has a high velocity of detonation and it is probable that, when detonated in a column of high explosives, detonation through its entire length would be practically instantaneous.

During the process of gelatinizing nitroglycerin, in the manufacture of either explosive gelatin or gelatin dynamite, minute bubbles of air are retained in the gelatinized mass. It is thought that this condition in gelatinized explosives merits considerable thought, particularly where such explosives are to be used in deep wells where hydrostatic pressure of high fluid columns must be contended with. Explosive gelatin, or so-called solidified nitroglycerin, is manufactured and wrapped in large sticks. Gelatin dynamite or so-called torpedo gelatin, is usually manufactured and wrapped in 50-lb blocks. In filling torpedo shells with either explosive, it is impossible to fill the shells completely in such a manner as to exclude air between the pieces or layers. Undoubtedly high hydrostatic pressures will tend to compress the air contained in the gelatinized mass or between layers of explosive in torpedo shells, which may result in the collapse of a loaded shell or cause local heating and oxidation in some portion of the explosive charge. Either one of these conditions may produce a premature explosion.

Probable Relative Size of Shot-holes

The probable size of the cavity resulting from the brisant or disruptive effect of high explosives in certain formations has often been questioned, and until recently little or no effort has been made to obtain measurements which could be used in estimating the result of shooting.

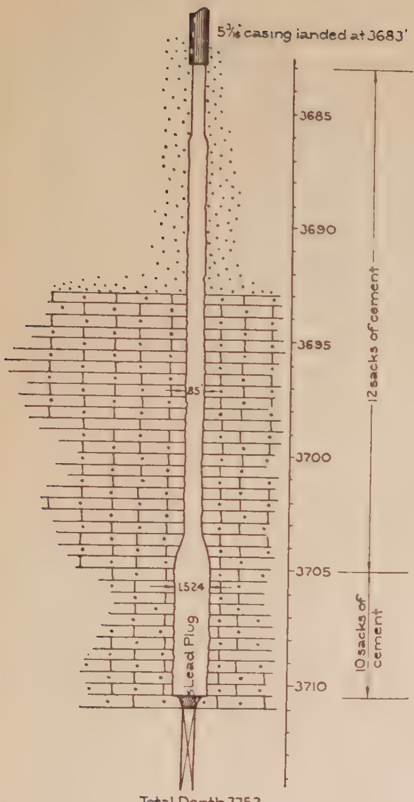


Fig. 11.

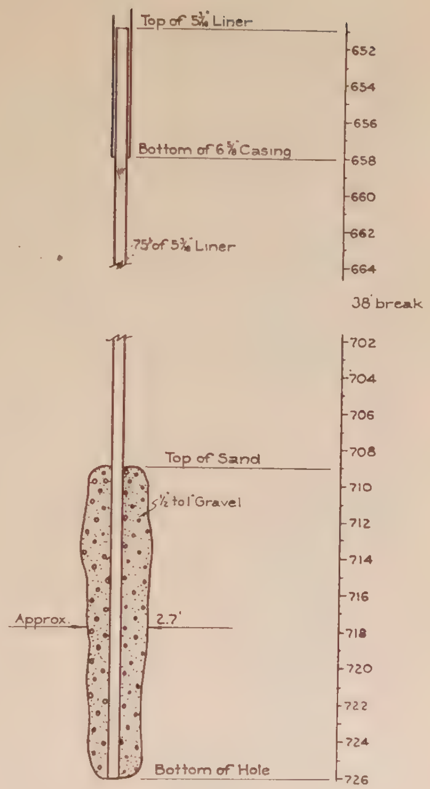


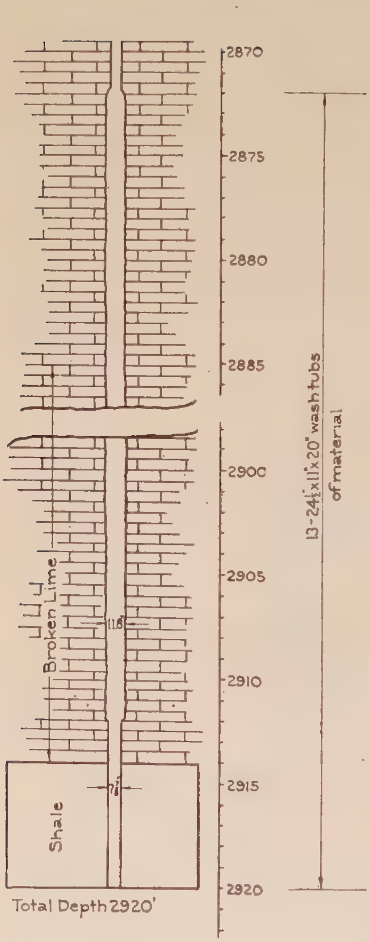
Fig. 12.

Fig. 11.—Probable relative size of shot-hole, well No. 2, 17-32S-2E, Kansas.

Shot data: 3689 to 3698 ft., 10 qt.; 3689 to 3708 ft., 30 quarts.

Fig. 12.—Probable relative size of shot-hole, well No. 43, Butler County, Kansas.

Shot data: 709 to 724 ft., 15 quarts.



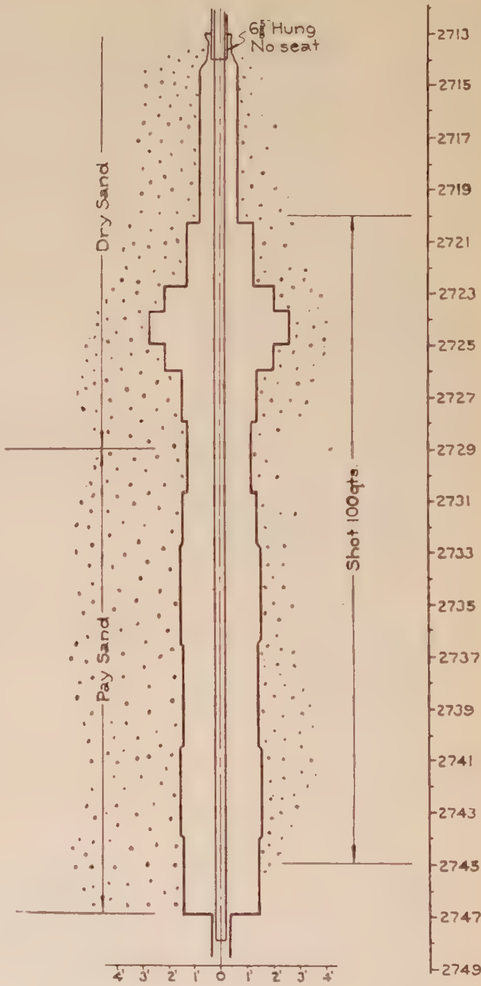


Fig. 13. Fig. 14.

Fig. 13.—Probable relative size of shot-hole, well No. 1, Sec. 55-Blk.B2-H & GN RR Survey, Gray County, Texas.

Shot data: 2872–2912 ft., 100 quarts.

Fig. 14.—Probable relative size of shot-hole, well No. 2A, Butler County, Kansas.

Shot data: 2720 to 2745 ft.; 100 qt.; average diameter of shot hole, 3.026 ft.; 8.6 cu. yd. gravel used.

Interesting data, showing the amounts of various materials necessary to fill up these cavities by stages during subsequent plugging operations or the work of filling the cavities with gravel for their preservation are presented in Figs. 11, 12, 13, and 14. The irregularity of the holes is no doubt due to variation in the character of formations or to the existence of bedding planes where the effect of certain portions of the shot was more pronounced. In this connection it may be said that the calculations are probably low, because the materials placed in the shot-holes were not driven down to the density of the formation in place.

While the results discussed should not be considered as a criterion of what may be expected in all cases and under all conditions, they do give some indication of the disruptive effect of high explosives and the probable increased area of drainage from the face of the sand exposed in the shot-hole.

Premature Explosions of Nitroglycerin in Wells and on the Surface

Following are given in brief 16 examples of premature explosions of nitroglycerin in wells and on the surface in Kansas, Montana, Oklahoma, Pennsylvania, and Texas:

1. Healdton field, Oklahoma: oil company's lease crew was preparing to shoot off string of "frozen" casing. A shell loaded with dynamite exploded at top of hole. It is thought fuse burned too rapidly. Three men were killed and one severely injured.

2. Torpedo company's nitroglycerin factory near Bartlesville, Okla., blew up and was completely demolished. In firing up boiler with oil a jack rabbit became saturated and ignited. The blazing rabbit ran under the factory floor setting the building on fire.

3. Torpedo company's storage magazine on Turkey Mountain, near Tulsa, Okla., exploded with loss of one life. The magazine is reported to have contained 350 qt. of the explosive. Cause of explosion unknown.

4. Six persons, including a woman, were killed in a premature explosion which occurred when a shooter started to pour nitroglycerin into a torpedo shell on the Stone farm near Franklin, Pa. It is reported that the explosive had been thawed out at the property, having arrived in a frozen condition. Cause of explosion undetermined.

5. Torpedo company's storage magazine on Turkey Mountain, near Tulsa, exploded. A stock-hauler had gone to magazine to haul 300 qt. to an Okmulgee, Okla., magazine. It is reported that all "stock" in the magazine, aggregating over 400 qt. was frozen. Not enough of stock-hauler's body was found to make identification possible. It is thought a container of the explosive was dropped during loading of the stock truck. Property damage extensive.

TABLE 7.—*Well Data for Poteau, Oklahoma, Gas Field Showing Gas Volumes before and after Shooting*

Well No.	Farm	Location (Sec.-Twp.-Rg.)	Sand, Ft.	Volume before Shooting, Million Cu. Ft.	Shooting Record: Date	Shooting Record: Gelatin, Lb.	Shooting Record: Dynamite (60%), Lb.	Shooting Record: Depth of Shot, Ft.	Volume after Shooting, Million Cu. Ft. Daily
48	Tucker	25-7-25	1328 to 1642	½	7/21/24	1600	150	1400 to 1560	1½
33	Tucker	3-8-26	1325 to 1528	Show	7/3/23	850	150	1390 to 1500	¾
43	Tucker	4-7-26	1311 to 1434	Show	3/3/24	800	175	1380 to 1420	Plugged
24	Tucker	3-7-26	1339 to 1478	Show	3/20/22		2500	1339 to 1409	Plugged
36	McDow	35-8-26	1307 to 1439	¼	9/1/23	1400	325	1369 to 1489	3½
32	Moneyham	32-8-27	1350 to 1371 1540 to 1575	None	3/6/21		1700	1350 to 1380 1469 to 1534	Plugged
8	Durant	23-7-26	1423 to 1628	¾	6/15/16		2000	1423 to 1688	6¼
49	Hunt	25-7-26	1303 to 1643	1	10/1/24	1600	250	1309 to 1509	2¾
34	Holton	34-8-27	1294 to 1480	¼	3/10/23	1300	100	1365 to 1475	2½
18	Littman	18-8-27	1425 to 1595	Show	8/19/22		750	1470 to 1569	½
26	Littman	18-8-27	1981 to 2016	Show	10/25/22		600	1970 to 2045	¾
32	McMurtry	35-8-26	1314 to 1670	Show	3/7/23	1000	250	1340 to 1665	1½
20	Cricklin	28-7-26	1611 to 1811	¼	9/24/20		1900	1665 to 1806	1½
10	Hughes	23-7-26	1510 to 1598	½	1/4/18		1250	1520 to 1590	5
44	Merriman	35-8-26	1281 to 1475	¾	3/20/24	1200	200	1304 to 1410	4
42	Merriman	35-8-26	1339 to 1474	½	1/28/24	1300	250	1339 to 1470	2½
34	Merriman	35-8-26	1334 to 1537	½	7/17/23	1200	325	1334 to 1485	4¼
19	Robbs	26-7-26	1445 to 1575	Show	7/13/20		2100	1479 to 1611	1½
18	Robbs	26-7-27	1435 to 1611	Show	4/18/20		3000	1423 to 1590	3
51	Babb	25-7-26	1350 to 1609	½	11/12/24	700	125	1400 to 1470	1½
21	Hill	22-7-26	1598 to 1840	Show	1/13/21		2800	1598 to 1829	1¾
50	Hitchins	25-7-26	1324 to 1605	1½	10/16/24	1600	225	1325 to 1595	1½

6. Torpedo company's nitroglycerin factory near Jefferson, Kan., was completely destroyed when charge of nitroglycerin in nitrator became ignited due to lack of agitation. A broken engine part necessitated the suspension of agitation at this critical time.

7. A loaded nitroglycerin truck, en route from Tulsa to the Burbank field, Okla., exploded on the Wynona-Hominy highway. Part of the truck is reported to have been blown through a nearby residence. The driver of the vehicle was blown to bits. Cause of explosion unknown.

8. A shooting truck, containing 80 qt. of nitroglycerin, exploded in the Bannatyne field, Mont., when the shooter attempted to remove two 10-qt. cans of nitroglycerin. One hundred and twenty quarts had already been placed in the well and the 80 qt. were to have been the remainder of the shot. Two men killed and one severely injured.

9. Seminole field, Oklahoma: Shooter had attached time bomb to 10-qt. torpedo gelatin shell and was preparing to lower both at the same time when explosion occurred. Two men were killed and one man severely injured. It is thought that time bomb, through an oversight, had been set for 10 min. instead of 1 hr. and 10 minutes.

10. Seminole field, Oklahoma: One shell containing 20 qt. of nitroglycerin had been lowered to the bottom of the well. A time bomb set for 2 hr. had been attached to second 20-qt. shell, which was being lowered in the hole. The shell exploded when it had been lowered about 650 ft., shooting off the $6\frac{5}{8}$-in. and $8\frac{1}{4}$-in. casings. Well probably junked. Cause undetermined.

11. A torpedo company's storage magazine near Haskell, Okla., exploded; reported to have contained 800 qt. of nitroglycerin. Impossible to ascertain cause, but company is of opinion that nitroglycerin thieves robbed magazine and then destroyed it.

12. Seminole field, Oklahoma: Forty quarts of nitroglycerin had been lowered to bottom of a hole. A time bomb had been attached to another loaded 20-qt. shell and was being lowered. Explosion took place when shell was 1000 ft. from top of hole, shooting off $6\frac{5}{8}$, $8\frac{1}{4}$, and 10-in. casing strings. Well later abandoned.

13. Seminole field, Oklahoma: Shell containing 20 qt. of nitroglycerin was being lowered. Explosion took place when shell was about 1200 ft. from top of hole. No time bomb was on this shell. Well finally repaired at great loss of money and production.

14. Borger field, Texas: Shot of 500 qt. of nitroglycerin had been placed in bottom of hole. Shooter had prepared mechanical time bomb and was screwing top on bomb shell when it exploded. Two men killed and one crippled permanently.

15. Borger field, Texas: Shot and time bomb had been placed in bottom of well. Casing was too close to shot and operator had to raise it several hundred feet. When casing was raised the gas from behind

it came into the hole and ejected last shell and time bomb from the well. The shell exploded when it struck the walking beam and killed three persons.

16. Oxford field, Kansas: Time bomb became unhooked while lowering in hole, exploded when it hit surface of fluid and severed $6\frac{5}{8}$, $8\frac{1}{4}$ and 10-in. casing strings. Well probably total loss.

17. Borger field, Texas: Loaded stock truck containing 500 qt. of nitroglycerin exploded on the public highway near Deal, Texas. Cause of explosion unknown.

Chapter II. Petroleum Research

Relative Propulsive Efficiencies of Air and Natural Gas in Pressure Drive Operations

By Harry H. Power,* Tulsa, Okla.

(Tulsa Meeting, October, 1928)

The relative merits of air and natural gas as propulsive agents in pressure drive operations have been discussed for a number of years. When air or gas is introduced into the sand, various factors lead the operator to the selection of what he believes to be the proper propelling medium; but when the question of relative drive effect is raised, several physical and chemical premises must be taken into consideration in arriving at a conclusion as to the superiority of one medium over the other.

Dow and Calkins[1] and Beecher and Parkhurst[2] have contributed fundamental experimental work on the effect of dissolved gas in lowering the viscosity and surface tension of crude oil. Herold[3] and Tickell[4] have indicated that whatever type of reservoir control obtains, gas plays other important parts in the movement of oil towards the well, namely:

1. The propulsive and expansive force of the gas.

2. The "Jamin effect," or resistance to the movement of oil in a porous media due to the formation of gas bubbles.

When quantitative studies are made, parallel conditions must be selected whereby we may say definitely whether air is superior to gas as a driving medium, or vice versa. Examples of similar conditions are not easy to find in the field. However, in the laboratory we can make determinations which may lead to general conclusions when applied to the field.

The experimental and research work described here was started at the laboratories of the University of California in January, 1927, and completed in private laboratories at Tulsa, Okla., in February, 1928. The apparatus used was designed especially for the work.

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* Gypsy Oil Co.

[1] D. B. Dow and L. P. Calkins: Solubility and Effects of Natural Gas and Air in Crude Oils. U. S. Bur. Mines *Rept. of Investigations* No. 2732 (Feb., 1926).

[2] C. E. Beecher and I. P. Parkhurst: Effect of Dissolved Gas upon the Viscosity and Surface Tension of Crude Oil. Petroleum Development and Technology in 1926, A. I. M. E., 51.

[3] S. C. Herold: Jamin Action—What It is and How It Affects Production of Oil and Gas. *Bull.* Amer. Assoc. Petr. Geol. (June, 1928) **12,** No. 6, 659.

[4] F. G. Tickell: The Function of Natural Gas in the Oil Sand. *Oil Field Engineering* (March, 1928) **3,** 11.

Studies were made of the influence of dissolved gas on certain properties and flow characteristics of gas-oil mixtures in order to determine and compare:

1. The effect of nitrogen and natural gas in solution on

(*a*) Gas-oil ratios.

(*b*) Gravity of gas-oil mixtures.

(*c*) Absolute viscosities of gas-oil mixtures.

2. The effect of nitrogen and natural gas in solution on the flow characteristics of an oil, saturated at various reservoir pressures, and propelled under constant head-pressure through a sand column at the outlet or orifice end of which pressure control, or so-called "back-pressure," was applied in constantly increasing increments.

3. The flow characteristics of the nonsaturated oil when propelled at constant reservoir or "head"-pressures to various orifice or "back"-pressures.

The oil selected for these experiments was a crude oil of 30.9° Bé., and was produced under vacuum so that little free gas remained dissolved in it at atmospheric pressures.

Two gases were selected for the experimental work—one, nitrogen, a gas of comparatively low solubility in oil, and the other, natural gas, of moderately high methane content and high solubility in oil. Nitrogen was selected, further, because of its similarity to air, and its elimination of the explosion hazard.

Apparatus

The apparatus (Fig. 1) consisted of the gas supply cylinder (*A*); the small oxygen cylinder (*B*) equipped with pressure gage (*E*); the pressure viscosimeter made up of gage (*F*); mixing chamber (*C*); lower chamber (*D*); equalizing tube (*H*); pyralin sight tube (*G*); the flow tube (*T*), equipped with gages (*M*) and (*N*); the necessary burettes (*P*) for collecting oil and gas; and the pressure bomb (*K*). Valves are indicated in the figure, No. 12 being an oxygen needle valve, and the remaining valves being of the heavy hydraulic type, with the exception of Nos. 1, 2, 3, 4 and 5, which were regular gas needle valves. Cylinder (*B*) and chamber (*C*) were of approximately 1-gal. capacity each, while chamber (*D*) was of approximately 0.2-gal. capacity. The flow tube (*T*) was water-jacketed to insure constant temperature, which involved isothermal expansion, and consisted of steel pipe $^{17}/_{64}$-in. inside dia., 86.25 in. long, equipped with gages as indicated, and connected to the pressure viscosimeter by means of the coupling (*S*). Oil sand of 48-65 mesh, carefully screened, washed and dried, was packed tightly in the flow tube. Cylinder (*B*) and gage (*E*) originally designed as a drop in pressure method of metering gas, were not needed, since the gas-oil ratio of the reservoir mixture was determined by means of the bomb (*K*).

Manipulation of Apparatus

Before beginning any of the oil runs, it was necessary to calibrate the pressure viscosimeter against a standard Saybolt viscosimeter in order that any number of seconds reading on the pressure instrument could be readily translated into seconds Saybolt.

Referring to Fig. 1, the following procedure was followed in making tests and runs. Exactly 1200 c.c. of 30.9° Bé. oil, produced in the field under vacuum, was poured through a filter into chamber (C) of the pressure viscosimeter by removing gage (F). The room temperature was kept constant at 70° F., and the oil and apparatus brought to the

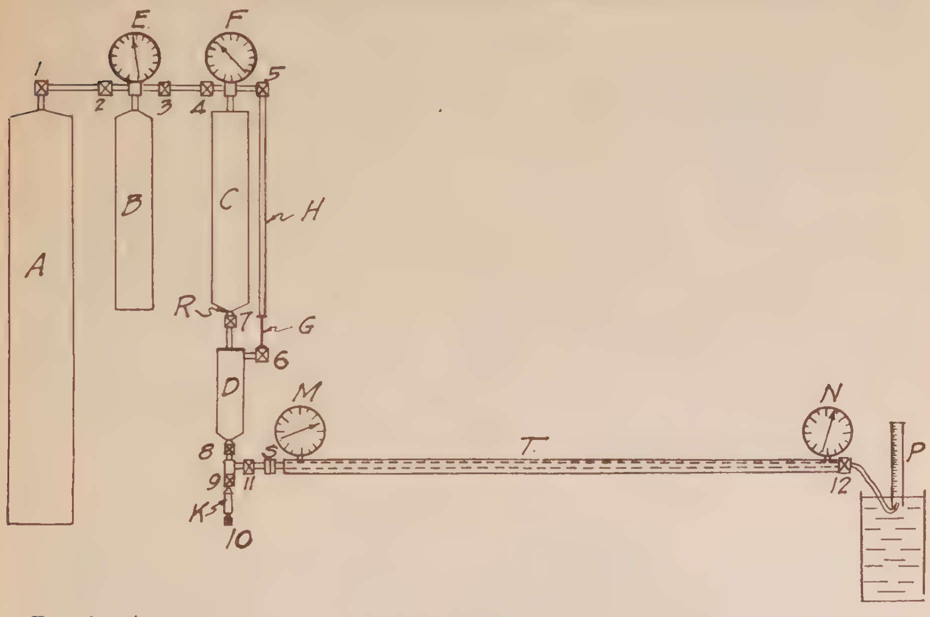

Fig. 1.—Apparatus used for experimental work with dissolved gas in oil.

same temperature. Gage (F) was then screwed into place again, valves 5, 6 and 7 closed, and the gas admitted to chamber (C) through valve 4 from cylinder (B) to the desired pressure. The entire pressure viscosimeter was hung on a pivot and the oil was thoroughly mixed with the gas by shaking the apparatus about this pivot. When the gage (F) no longer showed a drop in pressure, that is, when the desired saturation pressure remained constant, the oil was considered to be saturated. Before mixing, chamber (B) was disconnected from chamber (C) at valve 4. After the oil became saturated, chamber (B) was again connected, and the pressure in (D) equalized to that in (C) by opening valves 4, 5 and 6 cautiously. Valve 4 was then closed and valve 7 opened suddenly as the stop watch was started and the number of seconds noted for the oil to fill chamber (D) and rise to the pyralin tube (G).

The flow tube (T) was then connected by means of the coupling (S), and the oil permitted to flow until the sand in the tube was saturated and a uniform condition brought about at the desired efflux pressure indicated by gage (N). The water surrounding the flow tube was maintained at 70° F. Throughout an entire run, the reservoir pressure, or "pressure head," was kept constant by admitting gas into chamber (C) from cylinder (B).

P was an inverted graduate used as a burette in water of constant temperature (70° F.). The oil and gas mixture was conducted from the reducing valve 12 through a rubber tube to the bottom of the burette and permitted to replace the water in P, the gas rising to the top and the oil lying above the water and under the gas. Readings were taken every 15 min. and recorded, and the final reading in the case of the nitrogen runs taken several hours after the run, and in the case of natural gas runs at least 1 day after the run. The final volume of gas was corrected to sea-level basis and 70° F.

By pinching valve 12, pressure control was maintained at any desired gage reading indicated by (N).

After the desired production of oil and gas was obtained, bomb (K) was screwed to the bottom of the viscosimeter and filled with oil and gas at the saturation pressure indicated at (F). The bomb was then disconnected and the oil and gas permitted to escape into a burette. The volume of the bomb was known, also the volume of the oil and gas, and the oil-gas ratio and gravity of the original oil-gas mixture were then readily calculated.

Data Obtained

Ninety-three runs were made throughout the course of the laboratory work, a run being designated a measured flow of oil and gas from a given reservoir pressure to a given control pressure at the point of efflux. The data obtained are recorded in Figs. 2 to 9.

Solubility of Gases in Oil

Fig. 2 shows the solubility of the nitrogen and natural gas in the crude under consideration, and also shows the solubilities of air and natural gas in crudes of similar gravity as determined elsewhere. It is interesting to note that the solubility of nitrogen closely approximates the solubility of air, while the solubility of the natural gas used closely approximates the solubility of the natural gas as determined elsewhere.

Gravities of Gas-oil Mixtures

The gravities of the gas-oil mixtures were obtained by the use of the pressure bomb previously mentioned. The calculations involved

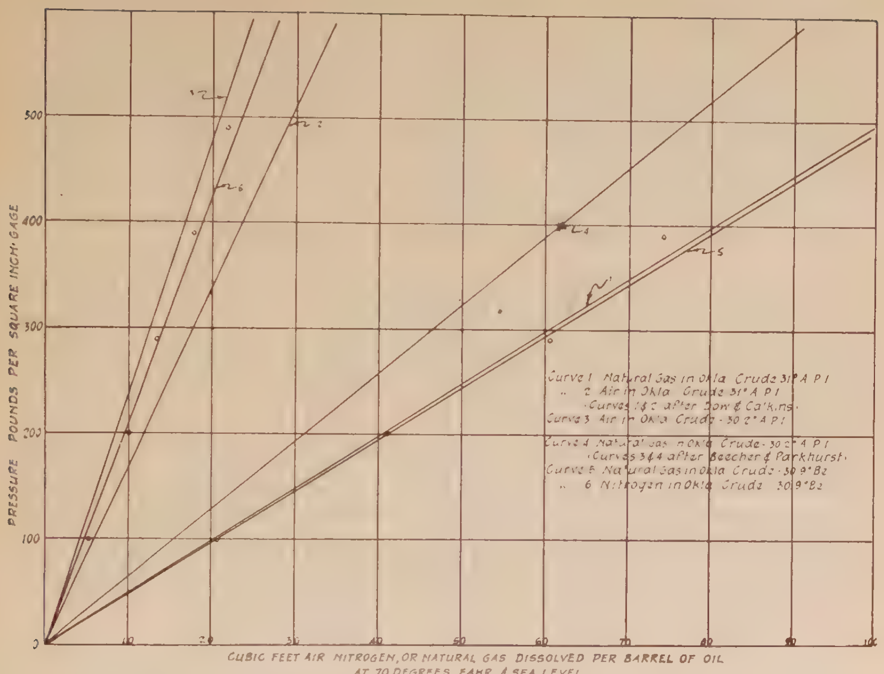

FIG. 2.—SOLUBILITY OF VARIOUS GASES IN CRUDE OILS.

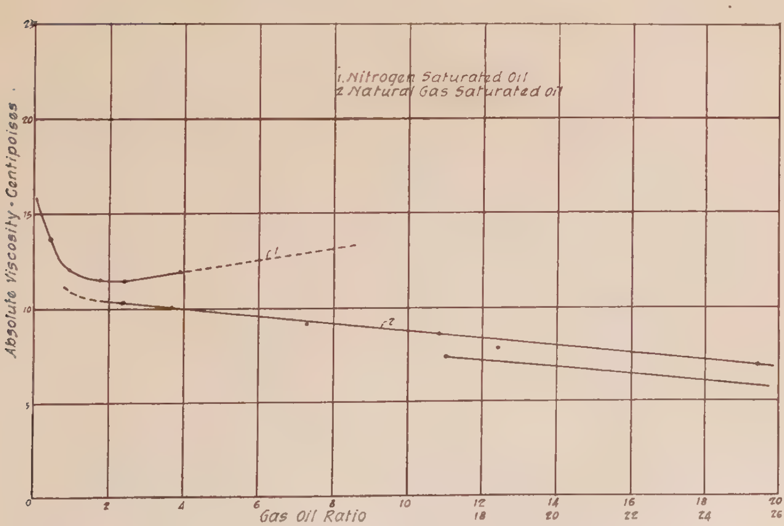

FIG. 3.—VISCOSITY GAS-OIL RATIO CURVES.

the gram-molecular weight of the gas absorbed in the oil, the weight of the oil produced from the bomb in grams, and the volume of the bomb. A curve was prepared from data obtained at different saturation pressures, and the gravity of the gas-oil mixture at the point of efflux from the flow tube was estimated by noting the gas-oil ratio and reading the gravity from this curve.

Viscosities of Gas-oil Mixtures

Fig. 3 shows the relationship between gas-oil ratios and absolute viscosities in centipoises. It is interesting to note that up to a gas-oil ratio of 2:1 the effect on viscosity of nitrogen and natural gas is very much the same, but when the gas-oil ratio increases beyond this the effect on viscosities is divergent.

The absolute viscosity of the oil-gas mixture at the point of efflux from the flow tube was estimated by noting the gas-oil ratio and reading from the curves of Fig. 3. Obviously, when the gas-oil ratio at point of efflux is above the reservoir gas-oil ratio, error is introduced, but in most cases the method is considered accurate enough for comparative purposes.

Interpretation of Results

In order to interpret the results obtained from the various runs, it was necessary to plot the data in some systematic form, see Figs. 4 to 9. The various figures are discussed in detail below.

Nitrogen Runs

Figs. 4 to 9 show the relationships between pressure differentials and rates of oil production, gas-oil ratios, absolute viscosities, and specific gravities of the various nitrogen-saturated oil runs.

Fig. 4 shows that the rate of production increases comparatively slowly when the difference between the reservoir gas-oil ratio and the efflux gas-oil ratio is greatest; when the difference between the viscosity of the reservoir gas-oil mixture and the efflux gas-oil mixture is least; and when the difference between the reservoir gas-oil gravity and efflux gravity is greatest. Figs. 5 and 6 exhibit these same characteristics in modified form.

Further, it will be noted that the first curve for nitrogen-saturated oil, Fig. 6, shows an increase in the rate of oil production at 150 lb. differential pressure. The other curves may have shown this increased rate of production at some critical control pressure, but inasmuch as control pressure was applied in 50-lb. increments, the critical pressure necessary to give maximum production may not have been used.

In each case, the efflux gas-oil ratio is always less than the reservoir gas-oil ratio, whereas the efflux gravity is higher than the reservoir gravity. Up to 200 lb. saturation pressure the efflux viscosity is higher (more viscous) than the reservoir viscosity, whereas above 200 lb. saturation pressure the efflux viscosity is progressively less than the reservoir viscosity. It may also be noticed in a general way that a given rate of production at the lower saturation pressures is produced under much less differential pressure than the same rate of production at the higher saturation pressures.

Natural Gas Runs

Figs. 4 to 9 show the relationships between pressure differentials and rates of oil production, gas-oil ratios, absolute viscosities, and specific gravities of the various natural gas-saturated oil runs. It is significant that the rate of production increased when the efflux gas-oil ratio was lowered, and when the efflux viscosity increased. It is evident that the effect of lowering the gas-oil ratio of the efflux mixture is of paramount importance in keeping the production rate at a maximum for any particular pressure differential.

Figs. 4, 5 and 6 show an increase in the rate of oil production when some control pressure is applied. At a saturation pressure of 485 lb., a control pressure of 50 lb. gave an increase in production, decrease in gas-oil ratio, and increase in viscosity. This is likewise true at a saturation pressure of 385 lb. At a saturation pressure of 200 lb. a control pressure of 25 lb. produced similar results. It appears, therefore, that there is a critical control pressure, depending upon the saturation pressure, at which there will be a maximum rate of production with the minimum expenditure of gas at point of efflux. There also appears to be a critical pressure differential at which the minimum production of gas takes place.

Viscosity does not appear to affect production rate as much as gas-oil ratio. An increase in viscosity accompanied by a decrease in gas-oil ratio at point of efflux is generally accompanied by an increase in rate of flow, tending to show that the amount of gas at the efflux end of the tube has more to do with rate of flow than the reduction in viscosity due to the dissolved gas.[5]

In general, a given rate of production at a lower saturation pressure is produced under much more differential pressure than the same rate of production at the higher saturation pressures. For instance, a rate of 4 cu. in. of oil per hr. at 485 lb. saturation requires 75 lb. differential pressure to produce it, whereas a rate of 4 cu. in. per hr. at 285 lb. saturation pressure requires 125 lb. differential to produce the same amount. This is contrary to the general results obtained with nitrogen.

[5] S. C. Herold: *Op. cit.*

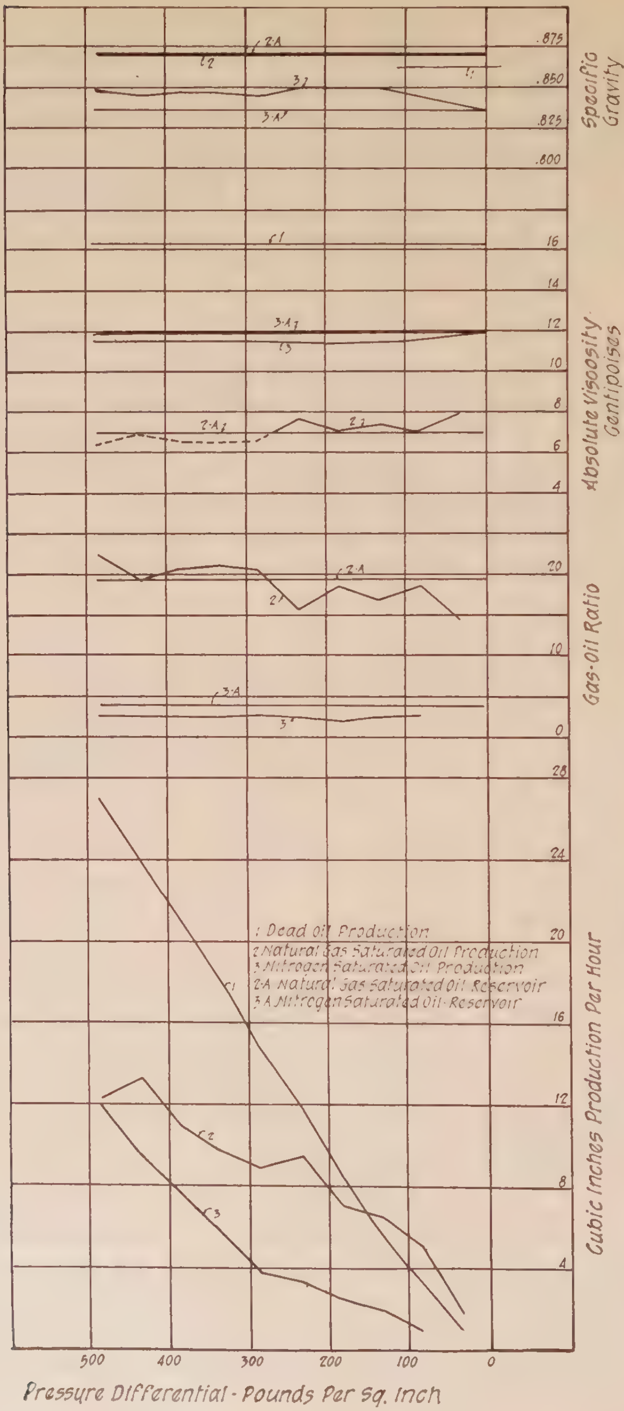

FIG. 4.—COMPARATIVE CURVES SHOWING PRODUCTION FROM 485-LB. GAGE RESERVOIR SATURATION PRESSURE.

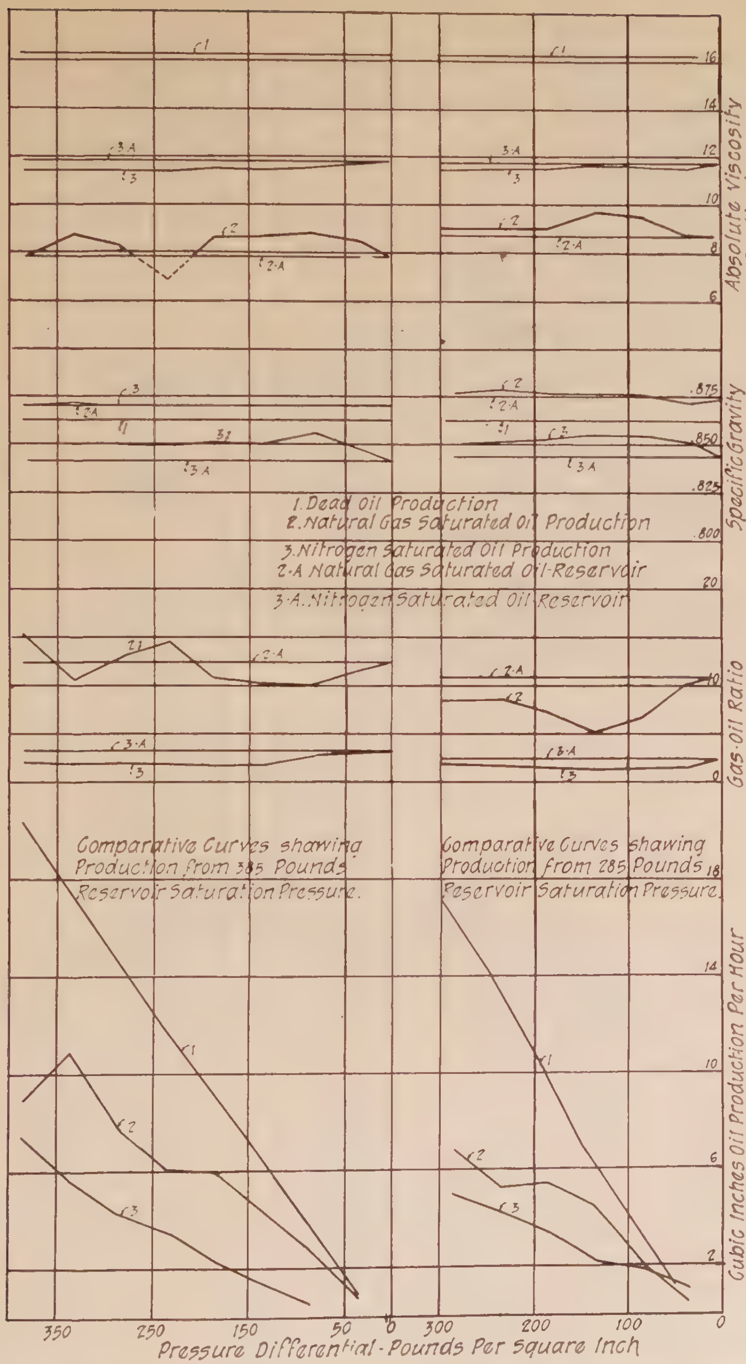

FIG. 5.—COMPARATIVE CURVES SHOWING PRODUCTION FROM 385 AND 285-LB. RESERVOIR SATURATION PRESSURES, RESPECTIVELY.

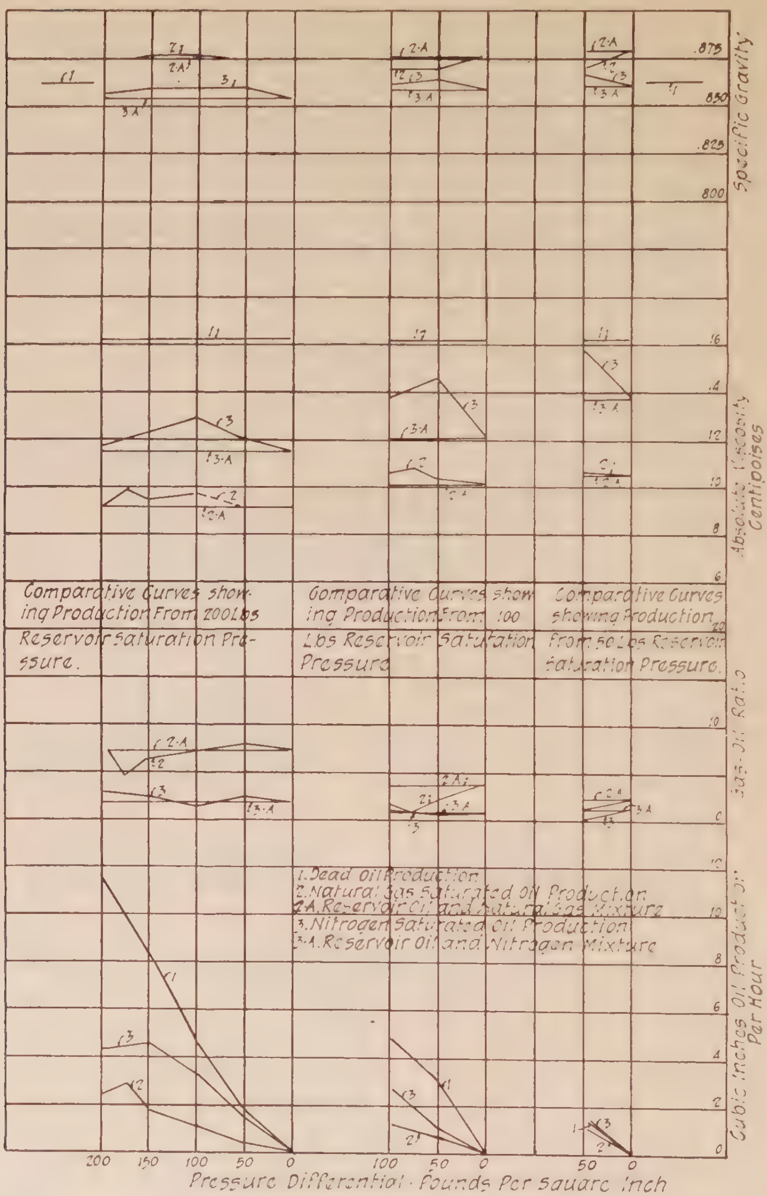

FIG. 6.—COMPARATIVE CURVES SHOWING PRODUCTION FROM 200, 100 AND 50-LB. RESERVOIR SATURATION PRESSURES, RESPECTIVELY.

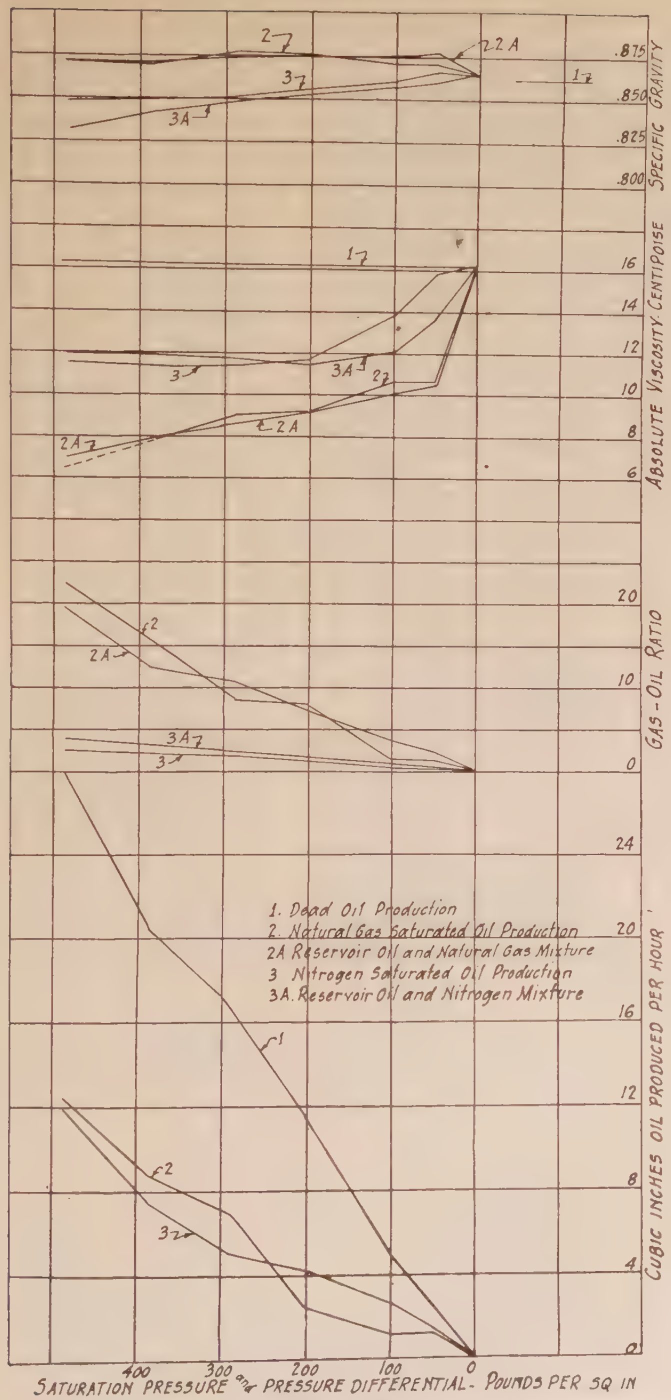

FIG. 7.—CURVES SHOWING FLOW RATES AT MAXIMUM DIFFERENTIALS FOR ALL SATURATIONS.

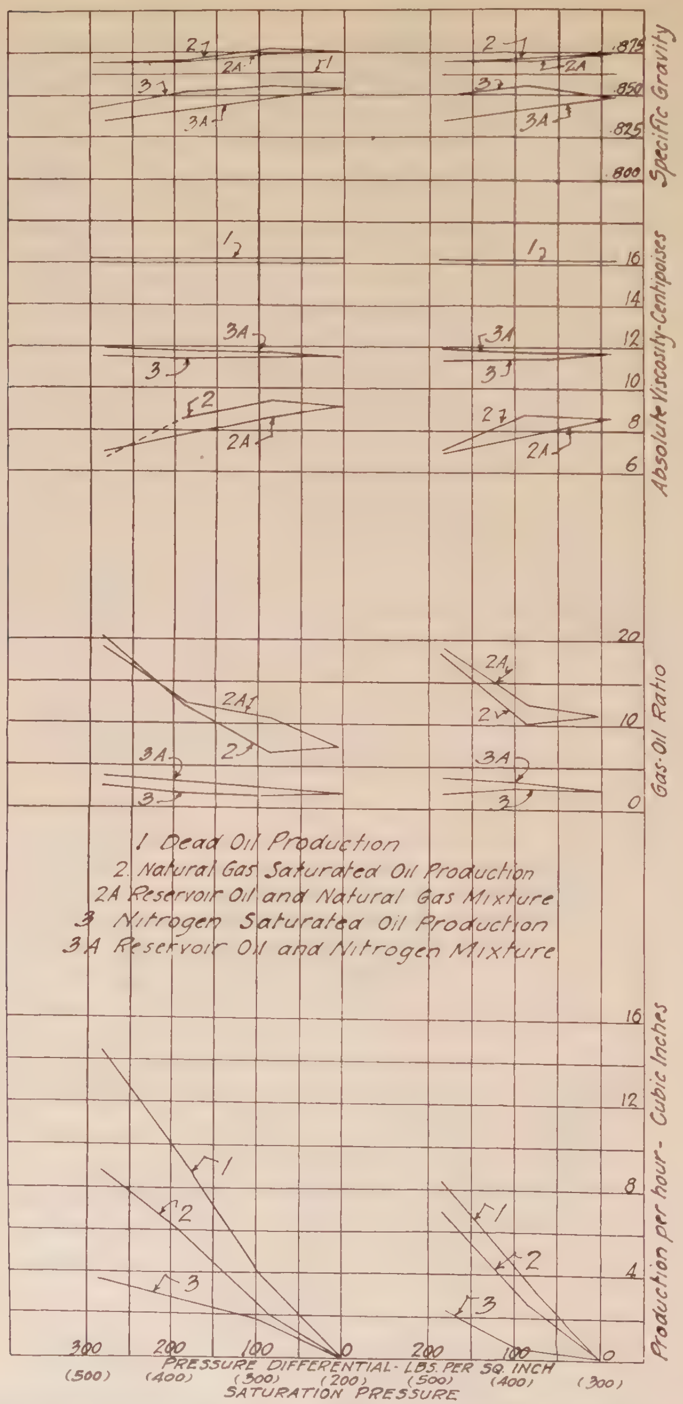

FIG. 8.—CURVES SHOWING FLOW RATES AT 200 AND 300-LB. CONTROL PRESSURES, RESPECTIVELY, FOR ALL SATURATIONS.

Nonsaturated Oil Runs

Figs. 4 to 9 show the results obtained from nonsaturated oil runs, rate of production being plotted against pressure differential. These runs were made by applying pressure on top of the oil in the pressure viscosimeter by means of nitrogen gas pressure, and maintaining this

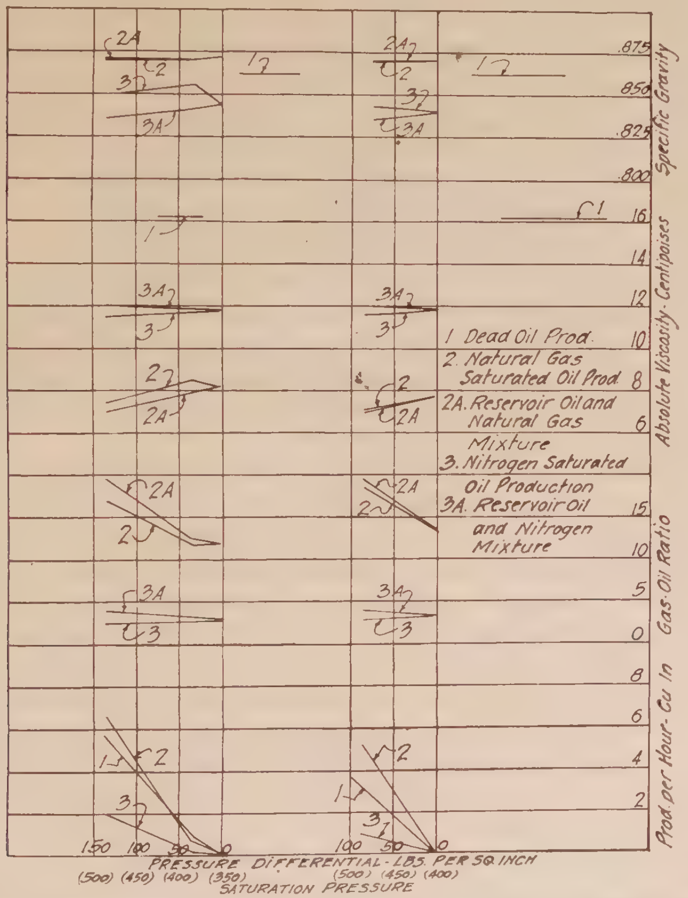

Fig. 9.—Curves showing flow rates at 350 and 400-lb. control pressures, respectively, for all saturations.

pressure at a constant amount without agitating the oil. No gas bubbles were observed at the point of efflux when the oil stream was directed into a water burette. Hence, the oil was considered to be nonsaturated. The same procedure was tried with natural gas as the pressure agent above the oil, but it was only a short time until gas appeared at the point of efflux. It is interesting to note the difference in production rates when using nitrogen and natural gas as the reservoir pressure agents.

The difference in the production rates is attributed to the gas resistance offered when the natural gas worked toward the orifice from the oil-gas interface.

Production Rates Using Nitrogen and Natural Gas as Pressure Agents

Pressure, Lb.		Oil Production, C.c. per Hr.	
Reservoir	Control	Nitrogen Pressure	Natural Gas Pressure
200	0	190	104
300	0	282	132

Comparison of Nitrogen-saturated, Natural Gas-saturated and Nonsaturated Oil Runs

(1) 485-*lb. Saturation Pressure.*—The curves of Fig. 4 show the effect of pressure differential on rate of production, gas-oil ratio, absolute viscosity and gravity, when natural gas and nitrogen were saturated in oil at 485 lb. gage pressure, and when nonsaturated oil was produced under this head pressure. For brevity's sake, the nonsaturated oil will be denoted as "dead" oil.

In all cases gas-oil ratios of the natural gas runs are much higher than those of the nitrogen runs; absolute viscosities of the natural gas runs are much less; gravities of the natural gas runs are considerably more.

The most significant feature of Fig. 4 is that the "dead" oil production curve in general is maintained at a much higher rate than the other curves. Another significant feature is that as long as the natural gas efflux gas-oil ratio remains under the reservoir ratio, the rate of production is maintained at a rate somewhat commensurate with the "dead" oil curve. On the other hand, the nitrogen efflux gas-oil ratio remains at all differentials below the reservoir gas-oil ratio, and the rate of production is maintained the highest when the difference between the two ratios is the least.

It is evident that the advantage in viscosity maintains the natural gas-saturated oil production at most differentials over the nitrogen production. However, at the greater differentials the two curves approach each other very closely, due, probably, to the resistance of gas evidenced by the gas-oil ratio at the efflux end of the natural gas flow tube, as compared to the gas-oil ratio at the efflux end of the tube in the case of the nitrogen runs.

When the viscosity of the "dead" oil is noted, it is again apparent that viscosity is not the main consideration in rate of production. The viscosity is much higher than in the other two cases, but no gas is in solution, and again it is inferred that gas in the flow tube is responsible in some way for the flattening of the production curves.

(2) *385-lb. and 285-lb. Saturation Pressure.*—The curves of Fig. 5 show the same general relationships as those of Fig. 4. There is a point at about 75 lb. differential on the 285-lb. saturation curves where the nitrogen and natural gas curves cross each other; in other words, at this point the two rates of production are the same.

(3) *200-lb., 100-lb. and 50-lb. Saturation Pressure.*—In Fig. 6, the nitrogen curves are above the natural gas curves. The viscosities of the natural gas mixtures are less than those of the nitrogen mixtures, and the gas-oil ratios of the nitrogen mixtures are lower than those of the natural gas mixtures. The gas in solution (and out of solution) at the efflux end of the flow tube appears to be the more important factor in controlling the rate of oil production.

In all of the above-mentioned curves it is pertinent to the object of these experiments to note the relative pressure differentials necessary in each case to produce a certain rate of oil. For instance, in Fig. 4, to produce at the rate of 8 cu. in. per hr. requires pressure differentials as follows:

Nitrogen-saturated Oil, Lb.	Natural Gas-saturated Oil, Lb.	Nonsaturated Oil, Lb.
395	205	175

Referring to Fig. 6, to produce at the rate of 2 cu. in. per hr. (200-lb. saturation pressure) requires pressure differentials as follows:

Nitrogen-saturated Oil, Lb.	Natural Gas-saturated Oil, Lb.	Nonsaturated Oil, Lb.
65	150	50

In one case, more energy is required to propel a given amount of nitrogen-saturated oil than a like amount of natural gas-saturated oil, and in the other case the reverse is true.

Flow Rates at Maximum Differentials for All Saturation Pressures

Curves indicating the flow rates of oil at maximum differentials of pressure for all saturation pressures are shown in Fig. 7. In these curves we may consider the reservoir pressure to have dropped to various saturation pressures from the highest pressure of 485 lb. down to atmospheric pressure, and as the reservoir or saturation pressure dropped the rate of production recorded as obtained with no control pressure other than atmospheric at the orifice, thus giving the maximum differential at each consecutive saturation. By so connecting up the points of the various runs curves were constructed somewhat simulating decline curves of an oil-gas reservoir.

According to Fig. 7, the nitrogen curve and the natural gas curve approach each other very closely. At the higher saturations the nitrogen-saturated oil has a much higher viscosity at both the reservoir end

and point of efflux than the natural gas-saturated oil, yet less of the nitrogen is at the efflux end of the tube, and for this reason chiefly the two curves approach each other. Thus, reduction in viscosity is opposed by gas bubbles[6] in the flow tube. The comparatively high rate of production of nonsaturated oil is exhibited at the various reservoir pressures.

Flow Rates at 50-lb. Control Pressure for All Saturation Pressures

The flow rates at 50-lb. control pressure for all saturations exhibit the same general characteristics as indicated in the curves of Fig. 7. At the lower differentials the nitrogen curve is above the natural gas curve. At these lower pressures there is not a great deal of difference in viscosity in the oils saturated with the two different gases. More gas is produced with the natural gas-saturated oil, and gas bubbles in the flow tube may retard flow. However, at the higher differentials gas bubble resistance[6] is offset to some extent by lessening viscosity due to natural gas saturation, and the natural gas curve is shown above the nitrogen curve and more or less paralleling the nonsaturated oil curve.

Flow Rates at 200-lb. and 300-lb. Control Pressures for All Saturation Pressures

The curves of Fig. 8 show that the natural gas-oil mixture in the flow tube is more homogeneous throughout the length of the tube under the high "back"-pressures, the viscosity advantages and control of excess bubble formation causing the natural gas curve to approach the nonsaturated curve, whereas the nitrogen curve remains some distance from the other two, due in all probability to the greater viscosity of the nitrogen-saturated oil as a main consideration.

Flow Rates at 350-lb. and 400-lb. Control Pressures for All Saturation Pressures

The curves of Fig. 9 show similar characteristics to those of Fig. 8. It will be noted that there is now a material difference in the gas-oil ratios as between nitrogen and the natural gas-saturated oil mixtures; also a material difference in the absolute viscosities. The natural gas-saturated curve has passed above the nonsaturated oil curve, whereas the nitrogen-saturated curve still maintains a more or less flattened inclination. For the first time the advantage that natural gas has in viscosity over the nonsaturated oil is coming into prominence in the favorable effect on the production rate. The control pressures are so high that gas bubble resistence[6] is at a minimum.

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[6] S. C. Herold: *Op. cit.*

Conclusions

From the experimental work performed, it is concluded:

1. That the solubility of natural gas in oil is much greater than that of nitrogen in oil at equal temperatures and pressures; and that the solubility of nitrogen in oil closely approaches that of air in oil.

2. That increments of dissolved natural gas lower the absolute viscosity of the oil progressively; and that up to a certain critical point increments of dissolved nitrogen in oil lower the absolute viscosity to a minimum, beyond which, additional dissolved nitrogen tends to increase the viscosity of the oil.

3. In the nitrogen runs, the efflux gas-oil ratio bears a relationship to the rate of production; the absolute viscosity of the oil throughout the length of the flow tube is also apparently directly related to the increase or decrease in rate of production at any given saturation. In a general way, a given rate of production at the lower saturation pressures is maintained under much less differential pressure than the same rate of production at the higher saturation pressures.

4. In the natural gas runs the efflux gas-oil ratio and the absolute viscosity of the oil throughout the length of the flow tube have a direct relationship to the rate of oil production. The so-called Jamin effect,[7] or bubble resistance, at the efflux end of the tube appears to be of much greater consequence in the majority of runs using natural gas than in the corresponding runs using nitrogen. However, high pressure control applied at the orifice tends to decrease this effect when natural gas is used as the propulsive agent. In a general way, a given rate of production at a lower saturation pressure is maintained under much more differential pressure than the same rate of production at the higher saturation pressures.

5. Up to a certain saturation pressure (in this experiment 200 lb.) nitrogen is superior to natural gas as a propulsive agent. It may be significant that up to a saturation pressure of 200 lb. the viscosities of the gas-saturated and nitrogen-saturated oils are very close to each other, while the Jamin effect when using natural gas would be greater than when using nitrogen as a propulsive agent. Less energy is required to move a certain amount of oil per hour using nitrogen.

Above a certain saturation pressure (200 lb.) natural gas is superior to nitrogen as a propulsive agent. Less energy is required to move a certain amount of oil using natural gas.

6. There is a critical saturation pressure and a critical pressure differential at which both nitrogen and natural gas produce oil at the same rate.

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[7] S. C. Herold: *Op. cit.*

7. Volume for volume, nitrogen is superior to natural gas as a propulsive agent at all pressures.

8. As the main evidence of Jamin effect, the curves for nonsaturated oil, when compared with those for saturated oil, show strikingly that bubble resistance is of material consequence, especially when we consider that the nonsaturated oil had a much higher viscosity than either the nitrogen or natural gas-saturated oil. A gas-saturated oil having the advantage of lower viscosity can show a production rate commensurate to or greater than a nonsaturated oil under like pressure control only when bubble resistance is reduced to a minimum by means of high pressure control at the orifice.

9. At any given saturation pressure there is a critical point of pressure control, usually above atmospheric pressure, where the maximum rate of production is obtained with a saving in gas over that produced at atmospheric pressure.

10. At any given saturation pressure there is a critical point of pressure control, usually above atmospheric pressure, where the minimum rate of gas is produced with the oil.

11. From an interface between gas and nonsaturated oil, natural gas has a tendency to permeate into and through the oil at a greater rate than does nitrogen.

The above conclusions indicate in the field that:

1. Up to a certain saturation pressure, air is more efficient than natural gas as a repressuring agent, and above this pressure, natural gas is the more efficient, particularly when pressure control methods are employed.

2. The rate of oil production and ultimate production is increased, and the rate of gas production is decreased by proper pressure control methods at the well, where natural gas under pressure acts as the propulsive agent.

(*a*) Pressure control methods keep the gas in solution, thereby maintaining the viscosity and surface tension of the fluid more nearly constant from the interior portions of the reservoir to the well.

(*b*) Pressure control methods reduce bubble resistance.

(*c*) As a result of the effects of (*a*) and (*b*), less energy is required to propel a given amount of oil per unit of time.

3. That any process of recovery employed which will give a direct push or so-called "piston effect" to the oil without causing gas to permeate the oil body near the well will result in a materially greater rate of production. From this point of view, where conditions are favorable for a water drive, a greater rate of recovery would be possible under a given water head than under a corresponding head-pressure due to gas, *unless* the gas could be prevented from permeating through the oil to the well.

DISCUSSION

J. O. LEWIS,* Tulsa, Okla. (written discussion).—Mr. Power's paper outlines results from 93 experiments which give every evidence of being carried on with care and intelligence. The purposes of the experiment, the manner of conducting and the materials and methods used are somewhat different from those of Mr. Mills and his associates[8] and therefore cannot be directly compared in a quantitative sense, but the two do relate in outlining certain principles. In a paper like this it is necessary to give careful study both to the data obtained from the experiments and to the conclusions reached by the experimenter. The interpretation of the results is fully as important as the experiments themselves. Such investigations as those by Power and Mills will constitute the factual basis for working out the correct principles of oil recovery, but careful analysis and interpretations of both the experimental and observational data will be necessary also; otherwise, erroneous conclusions may be made.

Mr. Power confirms previous experiments as to the relative solubility of natural gas and nitrogen but he brings out a new point in showing that volume for volume, nitrogen lowers the viscosity almost as much as does natural gas, up to a critical point, above which viscosity increases again. There may be a question whether the effects would be the same with air, as the oxygen in the air has a chemical as well as physical effect and therefore may give different results, though Mills and his coworkers report no important change from air. It is to be noted in the foregoing that the statements about the relative effect on the viscosities of oil by natural gas and nitrogen are based on the quantity of gas in solution. Based on relative pressures, the natural gas is far more effective in reducing viscosities, as it is more soluble.

After confirming the fact that gas in solution decreases viscosities of the oils, Power experiments with the influence of the decreased viscosity on the efficiency of oil propulsion through the sand. His findings confirm previous statements of the reviewer, that the importance of reducing viscosity was being greatly overestimated. Power also confirms the reviewer's statements as to the relative propulsive efficiency of air and natural gas; that is, of slightly and highly soluble gases. As it was impossible in the experiments to differentiate the effects of reduced viscosity and increased solubility, it is necessary to consider the results together.

The effect of using the more soluble gas under conditions that give reduced viscosity is to get a more rapid propulsive rate under the same head pressure but a much lower mechanical efficiency. By mechanical efficiency, the reviewer means the relative energy required to expel a given quantity of oil. Power shows the gas-oil ratio for natural gas to be very much greater than for the less soluble nitrogen, being as much as 7 or 8 times in some experiments.

Mills and his associates show approximately the same thing, but they also show that as the sand becomes depleted there is comparatively little difference in the efficiency of the two gases. This substantiates field observation in repressuring. Power shows that the relative efficiencies become less favorable for the natural gas as the head and differential pressures become higher.

In 1916 the writer conducted a series of experiments for the U. S. Bureau of Mines, the results of which were never published because they were pioneer tests made in a crude way and never completed, as the reviewer afterwards was transferred to other work. The results coincided with the results of Power's and Mills' experiments.

The explanation is that a more soluble gas passes through the oil in a state of solution, therefore its mechanical energy is not usefully employed to displace the oil. However, when the sand is depleted, most of the gas slips through the center of the pores and thus is mechanically wasted, which causes less difference in efficiency. In a

* Petroleum Engineer.

[8] See page 334.

practical manner these experiments show that air would be more efficient in a field where the sand was still highly saturated with oil, but in a field that had reached an advance stage of depletion there would be little difference between the two.

The statements made by Power as to the effect of pushing dead oil out of the sand by gas and nitrogen is confirmatory of these statements. He shows that nitrogen is more efficient and that practically no nitrogen worked ahead of the oil, whereas considerable natural gas worked through the oil in a state of solution and came out ahead of the oil. This answers the apprehensions that once the gas has worked out of the oil in the sand, it would be impossible to get the gas back into solution within a practicable time. The reviewer's experience has been that without agitation it takes a long time to get gas into solution in a liquid contained in a vessel but when the oil is contained in the pores of a sand, the gas will go into solution readily. This is confirmed also by Mills' experiments.

However, the reviewer does not wish to appear as not favoring the use of back-pressure or the early application of repressuring methods, for as pointed out by Mills, early repressuring will for other reasons be more economical and in a practical way will generally result in the conservation of gas and result in less expense and more profits.

The greater recoveries from the less soluble gas have been in spite of the fact that the oil is more viscous than when gas is used. As previously stated, the lower viscosity made a higher rate of production but a less efficient recovery. These results also confirm the reviewer's experience. The reviewer has often been impressed with the fact that in heavy-oil fields the percentage recovery approached so closely to light oil fields when other conditions were similar. In the McKittrick, Sunset, Kern River fields in California and in the heavy-oil fields of Nevada County, Arkansas, the oil may be hundreds of times more viscous than in other fields producing from the same or similar sands; yet the percentage recovery appears to be almost as large in spite of the fact that there is far less gas accompanying the oil in the heavy-oil properties. The heavy oil certainly retards the movements of the oil and gas but it does not appear to let the gas slip through and be mechanically wasted to as great a degree. It is likely that there is an optimum viscosity which will give the highest percentage of recovery under conditions otherwise the same. If the oil is less viscous there will be too much mechanical wastage of gas and if it is more viscous too much of the energy will be used up in overcoming frictional resistance.

When it comes to the effect of back-pressures, Mills and Power do not reach the same conclusions, but this is probably caused in part by the manner of experimentation. Power concludes that there is an optimum back-pressure at which there is the lowest natural gas ratio. This has always been the opinion of the reviewer. There is probably an optimum differential pressure ratio under each condition. The distinction between differential pressure ratio and differential pressures should be noted; 100 lb. difference in pressure between 400 and 500 lb. absolute is quite different from between 115 and 15 lb. absolute. In the first case the expansion of the gas is only 20 per cent.; in the latter, it is nearly 700 per cent. increase. The relative energy released is shown by the relative expansion of the gas. This principle may be seen more clearly by remembering that to raise a gas from atmospheric pressure to 105 lb. absolute requires no more energy than to raise the same gas from 105 to 735 lb. absolute, but the differential pressure in one case is 90 lb. and in the other 630 lb. Only by keeping this constantly in mind can one gain the significance of the experiments which both Mills and Power have conducted on back-pressures.

The effect of different ratios of expansion on the gas-oil ratio can be seen most clearly in Mr. Power's Fig. 7. In this figure, the results of forcing the oil against atmospheric pressure shows that with a differential pressure of 485 lb. the gas-oil ratio is 20 to 1, whereas at 70 lb. the gas-oil ratio is between 2 and 3 to 1, although

the energy released in dropping from 485 gage to 70 lb. gage is just the same as in dropping from 70 lb. gage to atmospheric. By doubling the ratio of differential pressure, the gas-oil ratio is increased by four times. In other words, the gas-oil ratio appears to increase as the square of the ratio of differential pressure. The Bureau of Mines experiments suggest the same rule from the experiments which show that recoveries increase by approximately the square root of relative pressures. It would be desirable for further confirmatory experiments to be carried out in order to clearly establish this principle.

Mills in his experiments found no evidence of Jamin effect, whereas Power reports considerable evidence. The reviewer questions the evidence introduced by Power. Apparently Power overlooked the fact that in forcing the dead oil through the sand the velocity for a given rate of oil recovery is less than when gas is passing through the sand along with the oil. In Fig. 7 at 400 lb. pressure, the recovery rate of dead oil was approximately 22 cu. in. per hr. and when saturated with natural gas, oil recovery was approximately 9 cu. in. per hr., but with each cubic inch of oil there was 17 cu. in. of free gas. In spite of the fact that gas has a much smaller frictional coefficient than oil, it is clear the friction from this gas might alone account for the slower rate of recovery. Thus there is no way of telling how much if any of the difference in rate is caused by the Jamin effect as distinguished from the frictional resistance of the gas itself.

The reviewer has always questioned the importance placed upon the Jamin effect. That it exists there can be no doubt, but that in the field it operates quantitatively to the degree claimed is against the evidence found by experiments or from observations in the field. Without going into particulars, the reviewer wishes to state that were the quantitative results of the Jamin effect as large as has been claimed, the behavior of the wells would be quite different from what we know them to be. The Jamin effect, of course, results in retarding the flow of oil and gas through the sand, but in this sense it is inseparable from the other frictional factors. What the reviewer questions is whether an important static resistance is often built up in the oil sand that will inhibit the flow of oil and gas to the well. Mills and his coworkers show that it is questionable whether there is any Jamin effect under the conditions of their experiments.

The Jamin effect logically leads to the belief that dead oil would require less pressure and could be moved more rapidly than oil with gas after making allowances for increased velocity and friction due to the accompanying gas, but it is a fact often observed in the field and in experiments that it requires a higher pressure to force dead oil through a sand. The reviewer made one experiment where at 200 lb. he could not force dead oil into a block of sandstone, though once the gas started through, the gas could be forced in readily at 5 lb. In the Bradford field, a well which several years ago was tried out as a pressure well and took large volumes of air as low as 25 lb., required over 400 lb. to drive back into the sand the dead oil, which afterwards had accumulated in the hole, but once the face of the sand was uncovered and the air could enter, it would take large volumes of air at the former pressures. Many similar experiences could be cited.

The same critical resistance for dead oil is shown in some of the experiments by Power. The curve for the dead oil in Fig. 4 is approximately a straight line, but projected downward the line intercepts the differential pressure curve above the zero point. If allowance is made of this critical pressure of about 33 lb., the relationship between pressure and rate of flow follows the laws of Poisuelle and Slichter, which have been mentioned by Tickell. [9]

[Additional discussion follows on page 335.]

[9] See page 343.

Oil Recovery Investigations of the Petroleum Experiment Station of the U. S. Bureau of Mines*

By R. Van A. Mills,† Joseph Chalmers‡ and J. S. Desmond,§ Bartlesville, Okla.

(Tulsa Meeting, October, 1928)

[Because of the limited space in this volume and the fact that a description covering the oil recovery buildings and equipment (see page 4, *Technical Publication* No. 144) will be given in a forthcoming U. S. Bureau of Mines publication, and because the paper was published in detail as *Technical Publication* No. 144, and is available as a separate at the Institute, it is impossible to include here more than the following brief extract.]

Problems Being Studied

The selection of the first problems to be studied was based largely upon the following very practical questions asked by several of the largest operators in the Mid-Continent field.

1. What are the causes for the formation of excessive amounts of bad thick oil on properties that are being repressured with compressed air and how can this trouble be prevented?

2. Why, in some areas, does the oxygen in the air injected into an oil sand during repressuring operations apparently change to carbon dioxide? Is carbon dioxide formed by the oxidation of some of the oil in the sand? How can the formation of inert or low B.t.u. casinghead gas, loaded with nitrogen, carbon dioxide and oxygen, be prevented?

3. What percentage of the oil originally present in an oil sand can be recovered by the ordinary methods of operation when the gas originally dissolved in the oil is the main propulsive agent?

4. What percentage of the amount of oil produced by ordinary methods can be recovered under average conditions by repressuring a so-called depleted oil sand?

5. What are the relative propulsive efficiencies of compressed air and natural gas in repressuring operations?

6. What are the practical advantages of pressure maintenance and early repressuring as compared with late repressuring?

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* Published with approval of the Director, U. S. Bureau of Mines.

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DISCUSSION

[Includes also discussion of paper by H. H. Power, pages 313 to 333.]

H. C. George,* Norman, Okla.—Several years ago, at the University of Oklahoma we found, in using solid blocks of sandstone—sandstone that had 33 per cent. effective porosity and had two wells in it, and the entire block of sandstone enclosed in cement—that we recovered by air pressure 53 per cent. of the oil contained, and later by introducing water we recovered an additional 12 per cent., making a total recovery of 65 per cent. The oil used was 38° gravity crude. This block of sandstone was about 18 in. thick and the recovery was made over a period of about 10½ hr. by intermittent flow, under 5 lb. air pressure.

R. Van A. Mills.—The experiments described by Professor George emphasize a point that I have been trying to bring out. It is reasonable to believe that every set of experimental conditions or field conditions involving the recovery of oil must yield some definite recovery factor and also some definite retention factor for that particular set of conditions. The percentage oil recovery that Professor George got in his repressuring experiments comes surprisingly close to what we got out by our repressuring experiments, and suggests that the total ultimate recovery factor of 50 to 53 per cent. for repressuring may not be far off for conditions other than those in our experiments.

F. G. Tickell,† Stanford University, Calif.—Mr. Power has done an excellent piece of research and his data deserve close study. I can corroborate his experimental observation to the effect that gas-bubble resistance may be of much greater magnitude than oil-viscosity resistance. I think, however, that the distinction between interstitial gas bubbles and interstitial foam should be borne in mind because of the different phenomena accompanying the generation and movement of each substance. For example, permanence and durability in a foam demand low surface tension of the oil from which it forms, while the resistance of simple interstitial bubbles varies directly with the surface tension of the oil.

It is possible that a durable interstitial foam would form where natural gas is used and that simple interstitial bubbles would form where nitrogen or air is used. This may account for the different mobility-saturation curves exhibited by the two gaseous media, although it is equally likely that the difference is attributable to the opposing viscosity gradients.

I think that one improvement in the apparatus described would be the addition of some provision whereby the flow tube could be charged with the gas-saturated oil without drop in pressure and without allowing the initial formation of bubbles. In actual gas-drive operations it is conceivable that most of the gas acts as a propellant behind the oil and does not diffuse very far into the oil in advance of propulsion. It has been claimed that oil does not absorb natural gas quickly unless the two are agitated. I think however, that this point needs clarification for reservoir and well conditions. Mr. Power's observation is very interesting, in this connection, that natural gas, used as propulsive agent behind a column of dead oil, rapidly diffused through the column and appeared at the point of efflux.

With regard to the author's comment on the divergence of the nitrogen and natural-gas viscosity-saturation curves, it should be noted that many constituents of natural gas liquefy when compressed, and the viscosity of a mixture of oil and gas at any pressure may be regarded as partly due to dilution of the oil by a substance of greater fluidity. There is, however, opposing this diminution of viscosity the effect of pressure

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† Professor of Petroleum Engineering.

on the oil itself. That is to say, pressure alone would greatly increase the viscosity of the oil. The net effect at any pressure is the balance between these opposing tendencies. In the case of nitrogen (or air), easily liquefiable constituents do not exist, and the effect of pressure on the oil's viscosity is more quickly made evident.

In the case of natural gas and oil mixtures, presumably there is a point beyond which increase in pressure would cause increase of viscosity, but this point is, no doubt, above the pressures existing in present known oil reservoirs.

C. B. Williams,* Cisco, Tex.—I want to bring out the fact that although the conclusions reached regarding the efficiency of air as a pushing agent are perhaps correct, there are other considerations which are of greater importance from a practical standpoint.

There is considerable repressuring of the shallow sands near Cisco, Tex. Nearly all these sands carry some water. The use of air in the presence of water causes a corrosive effect upon working barrels, balls and seats, etc., which offsets any increased efficiency it may give as a pusher.

In pumping small wells, economical operation is of paramount importance. From our experience with the use of air for repressuring, the corrosive action is so great and the pulling of wells so expensive that it pays us to use gas, even though we have to purchase a small amount of outside gas to continue the recycling. We actually produce more oil per day by having fewer wells off and less pulling.

Air-gas mixtures cannot be safely recycled through the sand, neither can they be handled by gasoline plants, for fear of explosions. Hence the gasoline-laden air coming from the casingheads must be wasted into the atmosphere. In one pool where adjacent leases are being repressured, one using air and the other recycling casinghead gas, the gravity of the oil from the former has decreased from 40 to 37 during the past two years, while in the case of the lease recycling the casinghead gas, the gravity of the oil has shown a slight increase. In order to recycle an air-gas mixture without fear of an explosion, we add sufficient exhaust gases from the engine to maintain the percentage of CO_2 in the recycled mixture above the explosive limit.

E. O. Bennett.—We have found that where water is present it is impossible to use air, on account of economic factors, but have found it difficult to institute gas on account of its condition. We are able to trace the direction in which the gas travels.

S. C. Herold,† Stanford University, Calif.—A question has been raised as to the actual resistance of the "Jamin action." Having once differentiated between the static and kinetic effects of this action, we may conclude immediately that the latter effects correspond to a "high viscosity effect." They affect the rate at which the oil and gas move through the sands to the well. The bubbles cause the fluids to move as if the oil were more viscous than it actually is.

In any apparatus containing sand with oil and gas any static effect of Jamin action can be overcome by applying a sufficient pressure at one of at least two orifices. I believe Mr. Mills had no static effects of Jamin action in his apparatus with his orifices on the side of his container. We encountered none in a similar apparatus, similarly arranged. However, by placing the orifices at the ends of the apparatus, in line with the movement of the sand under the applied pressure, we had these static effects. The sand appeared to jam toward the output orifice and so place the grains in a fixed position, allowing them to hold the globules and bubbles in their distorted condition. Where the grains are loose, they appear to give way to the distortion of the globule, and let the gas by-pass the oil with ease.

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* The Texas Co.

† Petroleum Geologist.

There seems to be a doubt in the minds of some regarding the existence of Jamin action. Let me cite evidence in its favor:

1. In the gas fields of Ohio, Pennsylvania, New York, Canadian Provinces, likewise in those of Kansas, the rate of production curve underlies the pressure curve, when these are plotted in their percentage values. If Jamin action did not exist in these reservoirs, the rate of production curve would overlie the pressure curve.

2. In the same fields the rate of production plotted against pressure on logarithmic paper gives a straight line with a slope of three to two. If Jamin action did not exist in these reservoirs the slope of the line would be one to two, in accordance with Torricelli's theorem.

3. In the oil fields of Kansas and Oklahoma the rate of production plotted against time on logarithmic paper gives a straight line with a slope of three to one. If Jamin action did not exist in these reservoirs the slope of the line would be one to one.

4. In the Zoar storage field near Buffalo, N. Y., we have a beautiful example of parabolic relations between pressure and volume of gas within the reservoir. The parabola is traversed very accurately year after year in the operation of the field. If Jamin action did not exist here there would be straight-line relations between pressure and volume of gas within the reservoir, in accordance with what we normally expect from relations determined by Boyle's law.

5. In the gas fields of Ohio, wells have been abandoned as exhausted. Years later a fifth well has been drilled in the middle of squares formed by the old ones. Where the original pressures at the old wells were 500 lb., the new well likewise showed 500 lb. Jamin action provides for a definite drainage radius surrounding each well. If Jamin action did not exist in these fields the new well drilled in the center of four exhausted ones would show no pressure, for it would encounter a really exhausted reservoir.

6. In the Cushing and Salt Creek fields the edge water does not encroach upon the wells in the pool. If Jamin action did not exist in these fields the water would encroach in the manner of the Coalinga and new West Texas fields.

In many fields we certainly have Jamin action to hinder or to help us—either way we wish to consider it—while in many others we certainly do not have it. Where there is Jamin action our water troubles are at a minimum, and where there is none, our water troubles are at a maximum. Where there is Jamin action we must resort to repressuring or to flooding to obtain a fair percentage of recovery, and where there is none we simply take the oil as it comes, for nature is flooding already on a grand scale.

K. B. Nowels,* Laramie, Wyo.—I am interested in Mr. Herold's statements about the drilling of "five-spot" wells. My interpretation is that a very peculiar condition must exist in the field he mentioned, as there should be a more or less uniform pressure depletion throughout the entire sand.

In the Salt Creek field accurate pressure data were kept on about two dozen wells. At the time the records were started, the average closed-in pressure was close to 500 lb. This pressure has declined until at present the closed-in pressure is approximately 20 lb. Throughout the entire period of pressure decline it was found that every new well drilled had a closed-in pressure practically equivalent to the average pressure existing throughout the field at that time. In other words, we always found the pressure in new wells to be not above, but approximately the same as the pressures existing at old wells.

R. Van A. Mills.—In southeastern Ohio, on some very old leases, the pressure has declined to only a few pounds per square inch and production has fallen to the unusually low point of ¼ to ½ bbl. Now, I was working in that field and collected

* Engineer in Charge, Petroleum Research Office, U. S. Bureau of Mines.

samples of sand and found the sand to be almost completely plugged with calcium carbonate. Those wells could not produce, because the sand was plugged. The leases were situated on good structure which did not show on the surface and we recommended to the producers that they drill new wells between the old ones. They did and got 50 and 100-bbl. wells in this very old field.

The decline of these old wells did not indicate depletion—the sand was plugged and the old wells could not produce.

G. P. CRUTCHFIELD,* Albany, Tex.—Mr. Mills says that a cumulative gas ratio of 11,000 cu. ft. per bbl. was adopted as a practical limit for producing under repressure. I am sure that it will be of interest if he will explain the method used in arriving at this figure. Our experience with the Cook pool in Texas leads us to believe that we will have attained the practical limit long before this figure is reached. We are trying to estimate our future gas ratios under repressure conditions, and I would like to hear the experience of anyone who has worked with this problem.

R. VAN A. MILLS.—For purposes of comparison, we had to take something as an experimental end point. The cost of putting compressed gas or air into pressure wells is approximately 4 to 5 c. per 1000 cu. ft. in the Mid-Continent fields. It seemed to us that a cost of 44 to 55 c. would be enough to allow for the maximum cost of the air or gas produced with the oil and we selected 11,000 cu. ft. arbitrarily on this basis as an end point.

J. O. LEWIS,† Tulsa, Okla. (written discussion).—This paper, though termed a preliminary report, covers 130 experiments, which together with Power's, constitute an exceedingly valuable contribution to petroleum engineering. These experiments were conducted in a larger apparatus with a finer sand than Power's but with oil of about the same quality. The purposes were somewhat different, as they were directed toward finding the natural and repressured recoveries under different pressures and other conditions. The thorough and systematic manner in which the experiments were conducted leaves a feeling of confidence. If followed up, they should go a long way toward solving the obscure problems relating to the extraction of oil from the sands.

Of course, the same question applies to all laboratory experiments, whether or not the conditions are comparable to those in the field. For this reason the findings should be critically analyzed and the results compared with observational data from the field. To a large extent the value of this work as well as the value of the work of Power, will depend on the analysis and interpretation of the factual evidence obtained from the experiments. At the present stage of progress in petroleum engineering, there is more call for correct analysis and interpretation of the available data than there is for new data, as we have not assimilated the facts that are before us. Recent literature is full of cloudy thinking and of misleading generalizations from isolated facts. It has been like drawing a conclusion from a sentence isolated from its context.

The experimental data and the conclusions reached are so completely and clearly set out by Mills and his coworkers that it is necessary to comment on only a few points. The reviewer is much interested in the results of these experiments as they appear to conform quite closely to opinions he had reached as the results of his own experience in the field and laboratory. Among them is that air will deplete an oil of its gasoline fractions in the same proportion as gas. This is important, as it has generally been contended that gas will pick up gasoline vapors to a greater extent than air. Mills' experiments prove that at least under laboratory conditions this is not true

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† Petroleum Engineer.

and his findings are in accordance with the long accepted physical law that all gases will carry the same percentage of a vapor under like conditions.

The amount that oil swells when gas is absorbed under high pressure is a valuable fact, as is also the selective absorption in oil of the different constituents of a gas. The authors do not report any evidence of important changes of the physical properties of the oil caused by chemical action of the gas. The thickening of the oil after putting on pressure is usually a temporary condition caused by former bad conditions in the well, which are aggravated by the increased oil, gas, and water resulting from repressuring.

The relation of the gas volume to oil production given in Table 5 is suggestive. The gas-oil ratio increases to a maximum in the early life of the well, then decreases until it reaches a point as low as the point of beginning, but afterwards rises to an excessively high ratio. The relation, however, is not at all like that which has been supposed by arguing that, as the pressure in the pool goes down, there is less energy in each cubic foot of gas and therefore it takes more cubic feet of gas to move a barrel of oil, with consequently an increasing gas-oil ratio as the well gets older. What has been overlooked is that the greater energy at high pressure is used up largely in velocity. The meager field data which have come to the reviewer's attention have disclosed no regular relation of gas-oil ratios with declining pressure. The data show that sometimes the gas-oil ratio tends to increase and at other times that it decreases, but the changes in gas-oil ratio during the various stages of the life of the well are not as much as would be expected on the theory that more gas would be required because of less pressure. Whether this experimental relation is one that will be found generally true can hardly be said at this time. There should be more laboratory and field data analyzed.

The experiments on ultimate recoveries show a maximum of 40 per cent. at 800 lb. pressure and from this the authors conclude that "the natural recovery from oil sands may be somewhat higher than has been supposed by some engineers." The reviewer believes this is a generalization that should be questioned. It is a well known fact that the Wilcox sand gives recoveries above the usual, doubtless due to the character of sand, which is uniform and round, but still more important is the small scale on which the experiment was conducted. It is an axiom of mechanics that to move an object twice as far requires twice the force; therefore, to compare the final recovery from a tube of sand 5 ft. long to the natural recovery where the oil has to be moved 50 times as far is manifestly not justifiable. Cutler has shown that recovery under otherwise like conditions approximately varies inversely as the distance between wells.

The reviewer objects to the author's use of the term "by-passing." As previously used, the term by-passing refers to the air or gas passing through the member of the sand body offering least resistance. The tendency of the gas-oil ratio to increase in a uniform sand body as it is depleted should properly have another term, which is "slippage." In the latter circumstance the gas mostly passes through the centers of the depleted pores, leaving the oil clinging to the sand surfaces and in the angles of the pores. There is a very important practical distinction and it is desirable that the two terms be not confused.

The fact that the gas-oil ratio increases as the sand depletes is important in considering recovery problems. The reviewer found by his experiments that the ratio increased by hundreds and even thousands of times as the sand was depleted, when the same pressure was being maintained. This marks the inevitable economic limitation of recovery by gas pressure. The reviewer's experiments bear out those of the author's except that he noted no critical points as shown in Fig. 17, which the plotted data hardly justify.

The effect of the oil on the air is notable. The increase in CO_2 and 2CO and the decrease in O_2 has often been noted, especially in the western fields. This fact and the results of work by Beecher, Parkhurst, Dow, and Calkins, which show air to have a less favorable effect on viscosity than natural gas, have been used as arguments against the effectiveness of air as an expellant, but neither the authors' work nor Power's work supports this apprehension, nor does the reviewer know of any field evidence that does. Aside from incidental factors such as safety, air appears to be a better expellant than natural gas.

The experiments on the relative recoveries from repressuring at different stages of depletion are important. The results do not bear out the extreme concern taken by some engineers in recent discussions on conservation. The authors show a greater and more efficient recovery from late repressuring than from early repressuring.

This again illustrates the dangers from drawing conclusions from isolated facts. The fears that gas could not be gotten back into solution were based upon the slow diffusion of a gas under pressure into oil contained in a vessel, where there was no agitation. The influence of interfaces between solids and liquids on solubility was overlooked. It is well known that rough surfaces promote the ebullition of a gas from solution. To a greater degree the extensive surface areas of the sand grains promote both absorption and ebullition of gases. The authors', Power's, and the reviewer's experiments all show this. The effect of the sands' surfaces in promoting absorption is similar to agitation.

However, the time factor in recovery is such that there is no doubt that it is desirable to repressure early in the life of the field, and this is coupled with other practical considerations, which convince the reviewer that undoubtedly early repressuring will be more profitable and will result in higher actual recovery than by letting the field go through the long stage of depletion before starting rejuvenation.

The Bureau of Mines experiments give some data as to quantitative values of the Jamin effect. Under the conditions of experimentation, the final difference in pressure between the input and output ends of the flow tube should be the measure of the static resistance of the Jamin effect for the sand and oil used. In Table 5, the last figures given show a differential pressure of 0.8 lb., but this is not the final differential pressure, as both pressures were still declining and had not reached equilibrium. From personal communications the reviewer learns that in many other experiments carried on to longer periods the two gages come almost or quite to the same pressure. The gages used were not sensitive enough to measure very small differences but these experiments did show that the quantitative value of the Jamin effect was certainly very small and left valid doubt as to any proof of its existence under these conditions. That the Jamin effect exists in a linear series of pores, there can be no doubt, but these experiments put a question mark as to its existence, at least to an important extent, in a three-dimensional system of pores.

The reviewer wishes to commend Mr. Mills and his associates on what he believes to be the best experimental work so far done on oil recovery. The technique worked out for conducting such experiments is of especial importance. Unless experiments on oil recovery are carried on with a proper technique, widely misleading results may be obtained. Much experimental work is to be questioned because of faulty methods.

However, there is need of further analysis of the experimental facts. In plotting the relations between the facts presented, there are anomalies that need explanation. Evidently the experiments pass through critical conditions. These should be sought out and explained. Also, these experiments do not support many of the extreme views that have recently been advanced on conservation.

B. R. Stephenson,* Ponca City, Okla. (written discussion).—It is recognized that any percentage recovery found for a sand under laboratory conditions has a meaning only for that particular tube, sand, oil and temperature. If any one of these is changed, one gets a different percentage recovery for any one of the different experiments here reported. Since the temperature of nearly all producing sands is much higher than 70°, the temperature at which the experiments were conducted, the viscosity of the oil in the sand will be much less than that of the oil in these experiments. In a series of experiments performed by the writer it was demonstrated, as would be expected, that the permeability or ease of flow of oil through a consolidated sand is inversely proportional to the viscosity, that is, the lower the viscosity the greater the flow under the same external pressure conditions. If the viscosity is doubled the flow is cut in half.

In a consolidated sand under field conditions, where the porosity is lower on account of cementing, it has been found in laboratory experiments that the flow is less than in an unconsolidated sand. For a fine sand with angular grains the recovery is less than for a sand with rounded grains. These data do indicate, however, that when it is possible to find the percentage of recovery to be obtained from a given set of conditions we can feel certain that so much additional recovery can be expected from any given lease by merely subtracting. This percentage will not be 52, as indicated by the authors, except in conditions similar to those under which this experiment was performed.

The authors indicate that less oil was recovered in the early repressuring experiments than when the pressure was introduced late. This condition certainly would exist in the type of apparatus used since the outlet end was kept the same. At the higher pressures the gas would tend to blow through and would not obtain the same recovery up to the economic gas factor. In a set of similar experiments it has been demonstrated that if the pressure is maintained constant across the tube a higher gas pressure will cause a greater recovery with a lower gas factor. In one set of experiments it was found that for a 60 per cent. recovery with a low gas pressure the gas-oil ratio increased to 15,000 cu. ft. per bbl., while for the same pressure difference between the ends of the pipe with a higher inlet pressure the gas-oil ratio was only 6000 cu. ft. per bbl. for 60 per cent. recovery. The total recovery was also higher with the back-pressure than when no back-pressure was applied. A high differential should not be maintained but a high gas pressure with a high back-pressure produces a greater percentage of recovery in the laboratory than a low pressure. These data would indicate that early repressuring would not only produce the oil in a shorter time but would actually produce a greater percentage of recovery.

The greatest difficulty with laboratory work on small tubes is that none of them are large enough to allow the oil to settle to the bottom by gravity and thus leave the depleted area at the top of the sand that must exist in an oil field. A number of experimenters have demonstrated how high oil will stand on account of capillary attraction in an oil sand when it is partly depleted. In an old field where the sand is thick there would be a greater chance for the gas to by-pass than when the pressure is applied early, before the oil has had a chance to settle. This would be another argument in favor of early repressuring.

On page 27 of *Technical Publication* No. 144, the authors say that there has been an estimate made of the saturation of oil sands by examining cores. There is a serious question as to whether such core samples give any real information regarding the saturation of the sand. Samples are usually obtained with a core drill, the water of which washes out from 20 to 50 per cent. of the oil in the core, as was demonstrated by the writer in an experiment conducted expressly to determine this point.

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* Physicist, formerly with Research Dept., Marland Oil Co.

Any estimate of percentage recovery in the field is only approximate. Those made have usually been wrong partly because they have not accounted for the volume occupied by the gases and vapors in the reservoir together with the change in volume due to temperature change. The estimate has usually been made from the pore space, volume of sand, and the amount of oil measured in the tanks. This method is far from exact for a field like the Rainbow Bend, where a large amount of gas has been recovered which has brought out many gallons of liquid not measured in the stock tanks.

The equations of Fig. 15 for the percentage recovery at different pressures is simply a law of nature that must logically be obeyed for any given set of conditions of pipe. Many natural phenomena obey this law and in the oil field the pressure drop of a gas in flowing through a sand body together with that for oil and water also obey a logarithmic law. These data simply state that the percentage of recovery with pressure follows a law like this but the particular constants have no meaning when applied to a field problem, for these constants will change with every type of tube, sand, and oil that is used. As a rule it will be difficult to apply this relation, since the same sand and oil should be available. The Wilcox sand or the Hoover sand might be taken as an example where the increasing depth as one proceeds westward causes the pressure to increase. But at the same time the temperature is increased, so the oil is no longer the same, and thus the law derived in one section cannot be applied to another until more definite relations are established between all the factors.

The work to date is in the right direction but can be considered only as a progress report, with nothing settled.

Capillary Phenomena as Related to Oil Production

By Frederick G. Tickell,* Stanford University, Calif.

(Tulsa Meeting, October, 1928)

Petroleum engineers are displaying considerable interest in those fundamental properties of matter and energy that control the phenomena of oil and gas production. The subject is a difficult one to investigate by laboratory experiments for two reasons: (1) it is impossible to reproduce in the laboratory the scale of forces and dimensions that exist in the underground reservoir; (2) if we attempt to scale down the dimensions we are unable to reduce all proportionally. It is as if we tried to construct a model blast furnace for the reduction of iron ore, and reduced all lineal dimensions. We should find that the interstices between the miniature chunks of ore would not permit rapid transfer of gases, that combustion and heat transfer would not take place as in the full size furnace and that, in short, the contraption would not work. Just so, when we attempt to make a reduced scale oil field we find we must have, not only miniature reservoir and miniature wells, but "miniature" sand, oil, gas, etc. Much valuable work, however, has been done along these experimental lines and more will no doubt follow, but investigators should bear this point in mind and strive to attain dimensional homogeneity and dynamical similarity in order that their conclusions may be translated into terms applying to the oil reservoir. As Gibson says,[1] "These conditions are attained when all terms of the physical equation have the same dimensions, . . . when all corresponding particles of the two systems trace out similar paths and when the velocities are such as to make all corresponding forces acting on two such particles in the same ratio."

It is the purpose of this paper to discuss the mechanics of fluid movement as it pertains to the oil pool and to point out the complexity of the laws of fluid delivery under the conditions often found.

We have to do, fundamentally, with confined fluids, possessing potential energy whose expenditure is restricted by certain properties of the confining media and of the fluids themselves. The equation of motion and time is completely stated when we can assign values to the propulsive

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* Professor of Petroleum Engineering, Stanford University.

[1] A. H. Gibson: Principles of Dynamical Similarity with Special Reference to Model Experiments. *Engineering* (1924) **117,** 325–327, et seq.

forces and the opposing elements and know the way each varies with respect to the others. We are limited in our observations, however, to those we can make at or in the well; the rest must be inferred from laboratory experiments on the properties and motions of fluids under certain controlled conditions.

Fluids

The fluids in this system have as their principal components liquid petroleum, water and hydrocarbon gases. These may have different positions in the reservoir or they may exist together in such states of aggregation as gas bubbles in oil, water in oil emulsions, or gas in oil foams. The physical properties of these fluids may be widely different from one another.

Potential Energy

The potential energy of these fluids is caused either by density and gravity or by temperature. Thus, a closed (lenticular) sand reservoir filled with oil and gas derives its potential energy from compressed gases, and the compression may be due to the weight of the superincumbent rocks or to increase of temperature since the reservoir was filled. Again, an open type reservoir owes its potential energy to a hydrostatic column of liquid.

The Confining Media

The voids occupied by the fluids may be fractures or solution channels in massive limestone or shale or they may consist of minute interstices between the grains of a sandstone or sandy shale, the so-called porous medium. The reservoir may also be heterogeneous, part of the fluids, the oil and gas, for example, being contained in sandstone and the hydrostatic column principally in less permeable rocks. If this latter were the case we could remove the oil and gas much faster than the water could enter to take their places.

Oil and Gas Reservoirs

Reservoir systems may be classified as closed or open, and the open ones may be subclassified according to the manner in which the potential energy may find relief. The hydrostatic head may be held constant by meteoric waters or it may diminish at a rate dependent upon its rate of replenishment and upon the resistance offered to its flow into the space vacated by the oil and gas. This resistance may be caused by the impermeability of the rocks, or, where gas under pressure exists at a lower point in the structure, it will influence and be influenced by the pressure of the gas. In other words, the pressure of the gas is insufficient to keep the water out, but it holds it back; and the influx of water tends to build up

the pressure of the gas.[2] A proposed classification of reservoir systems based on these considerations is presented in the Appendix at the end of this paper.

Herold[3] states that these two "controls" cannot coexist in the same reservoir, and makes his classification of reservoirs and prediction of drainage areas on the basis of that premise. Uren, however, in commenting[4] on this point, says it seems probable that in most cases both types of drainage are operative simultaneously.

In order to analyze the condition more fully, let us consider in Fig. 1 two pistons (*A* and *B*) in a cylinder. *A* is connected to *B* by a short stiff spring and *B* is connected to the end wall (*C*) by a somewhat more limber but longer spring. *B* works in the cylinder against constant friction; *A* works against increasing friction in the direction of *D*. The two springs are considered to be compressed and have potential energy.

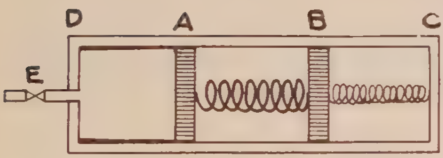

FIG. 1.—SPRING ANALOGY OF COMBINED-TYPE RESERVOIR.

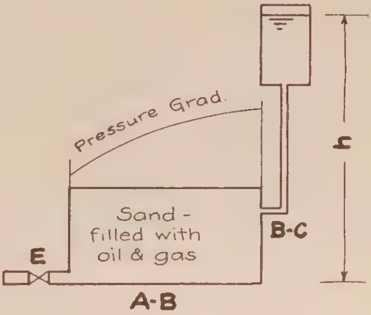

FIG. 2.—IDEAL COMBINED-TYPE RESERVOIR.

Now open the valve at *E*, allowing air to escape and the two springs to expand. The strength of each spring becomes less as expansion takes place and, at the same time, the resistance to *A*'s motion becomes greater. Due to its stronger spring, *A* will move faster with respect to *B* than *B* will with respect to *C*. At any instant, however, the velocity of *A* with respect to *C* will equal the sum of the two component velocities, and this velocity will be maintained longer than if *B* were stationary. When the spring *AB* can no longer expand against the increasing resistance between *A* and *D*, the velocity of *A* with respect to *B* will diminish to zero, and the work of expansion will be continued by the longer spring *BC* until

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[2] F. G. Tickell: The Function of Natural Gas in the Oil Sand. *Oil Field Engineering* (1928) **3**, No. 3, 11.

[3] S. C. Herold: Oil or Gas Well in a Sense is an Orifice. Fourth of a series of articles in *Oil & Gas Jnl.* (1924) **23**, 129, Par. 88.

S. C. Herold: Jam'n Action—What It Is and How It Affects Production of Oil and Gas. *Bull.* A. A. P. G. (1928) **12**, No. 6, 667.

[4] L. C. Uren: Dissolved Natural Gas in Oil in Ground a Force That Aids Production. Second article of a series. *Natl. Petr. News* (1927).

it also is stopped by the resistance. Substantially the same things would happen if the resistance between the pistons and cylinder were zero except that the springs would fully expand themselves before motion stopped.

Consider the analogy between this apparatus and the one pictured in Fig. 2. Here we have a tank filled with sand the interstices of which are filled with gas and oil at a pressure h. Connected to this tank by a small pipe is a tank of water. Open the valve at E and allow fluid to escape. The gas AB is an elastic substance compressed to a pressure h; and assuming that it may expand more rapidly than the water BC can enter to rebuild the pressure, the declining pressure of the water is always greater than the pressure of the gas. The velocity of efflux at E will decline less rapidly than if water did not enter; it is a continuous function of the pressure of AB and of the hydrostatic head remaining in BC. There will be a pressure gradient in AB with the lowest pressure at E, and this gradient will progressively flatten and extend towards BC as the fluid is withdrawn at E. The spring analogy is not offered as proof of the conditions in Fig. 2, but merely to prepare the way for the nonmathematical description of them.

The reservoir system in which exist both a hydrostatic column and liquids and gases confined and compressed in a porous medium, and ffnding concurrent relief, may be termed a "combined" type. The equation of motion and time will be quite different from those of the closed reservoir or the artesian reservoir and will be shown to be very complicated.

Resistance to Fluid Movement

Resistance to fluid motion is caused by friction between the fluid and its containing walls and by internal friction of the fluid itself. Where the interfacial tension between a liquid and solid is low, as is usually the case, the liquid will wet the solid and form an adherent film which will be practically stationary while motion takes place in the body of the liquid. Most of the resistance will then be due to internal friction of the liquid, or viscosity. The term viscosity, in its widest sense, may be applied to the internal friction of any aggregate of fluids, such as an emulsion or foam, that moves as a body. Anything that changes the resistance to flow may be said to change the viscosity.

Poiseuille[5] showed that the flow through a capillary tube is, other dimensions being fixed, directly proportional to the pressure difference and inversely proportional to the viscosity, and Slichter[6] showed that the same is true for the movement of water through sands. In the case of a gas-oil system, however, the viscosity is also a function of the absolute

[5] Rapport sur un Mémoire de M. le docteur Poiseuille. *Compt. rend.* (1842) **15**, 1167.

[6] C. S. Slichter: Theoretical Investigation of the Motion of Ground Waters. U. S. G. S. 19th *An. Rept.* (1897–8) Pt. 2, 301.

pressure. A pressure drop in a compressed gas-oil mixture in a porous medium results in loss of gas from the mixture (Henry's law), and that which still remains in the liquid phase has greater viscosity.[7] The gas that escapes still further contributes to the viscosity of the fluid because it is entrapped in the sand interstices and exists either as isolated gas bubbles in a dispersion medium of oil, or as bubbles separated by liquid lamellae of micronic or submicronic thickness (foam).

Jamin Effect

Jamin[8] was probably the first to call particular attention to the resistance offered by gas bubbles to the movement of liquid in a porous body. He was concerned with those cases where the gas bubbles in their spherical form would be larger than the capillary passages, and showed that their surface films resisted distortion and that work must be done to force them into capillary passages or to move them while they are already confined within these passages. The amount of work done on any bubble depends upon the amount of distortion the surface film must suffer; part of this mechanical energy is restored to the system when the bubble is allowed to resume its spherical form, but a small part is converted into heat energy, which may be conducted away from the system. Jamin showed that the aggregate force required to produce (and work required to maintain) motion in a system of this kind is of much greater magnitude than where there is liquid alone in the porous body.

Work of Surface Film Deformation

The experiments of Plateau[9] have shown how surface tension phenomena may be studied in the absence of the complicating influence of gravity. If a body of one liquid (say olive oil) is immersed in a larger volume of another liquid of the same density (say water and alcohol), the interfacial tension will cause the oil to assume the form of least surface, a sphere, and it will neither float nor sink. Work must be done on this globule to increase its surface, so that the surface resists extension and has surface energy. The unit value of this surface energy is called "surface tension" and is expressed as energy per unit of area (dimensions $FL \times L^{-2} = FL^{-1}$). The dimensions FL^{-1} express force per unit of length, and these are the customary units; that is, dynes per centimeter, with symbol T.

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[7] C. E. Beecher and I. P. Parkhurst: Effect of Dissolved Gas Upon the Viscosity and Surface Tension of Crude Oil. Petroleum Development and Technology in 1926, A. I. M. E., 58.

[8] M. Jamin: Leçons sur les lois de l'équilibre et du mouvement des liquides dans les corps poreux. Professées à la Société Chimique de Paris (1861).

[9] J. A. F. Plateau: Experimental and Theoretical Research on the Figures of Equilibrium of a Liquid Mass Withdrawn from the Action of Gravity. Smith. Inst. *An. Repts.* (1863–1866, incl.)

Since the surface of the globule is $S = 4\pi r^2$; where more oil is forced into the globule the rate of increase of surface with respect to radius is:

$$\frac{ds}{dr} = 8\pi r$$

and the rate of increase of surface energy is:

$$T\frac{ds}{dr} = 8\pi rT$$

or

$$Tds = 8\pi rTdr$$

Now the volume of the bubble is:

$$V = \tfrac{4}{3}\pi r^3$$

and

$$dV = 4\pi r^2 dr$$

Since

$$8\pi rTdr = 4\pi r^2 dr \times \frac{2T}{r},$$

$$Tds = \frac{2T}{r} \times dV.$$

The work performed is

$$\int Tds = \int \frac{2T}{r}\, dV = \int pdV$$

where p = excess of pressure in the globule; so that

$$p = \frac{2T}{r}$$

or $pr = 2T$ = a constant for the two fluids. If the globule is a bubble of gas, the same relation holds true but the bubble will have buoyancy and rise to the surface.

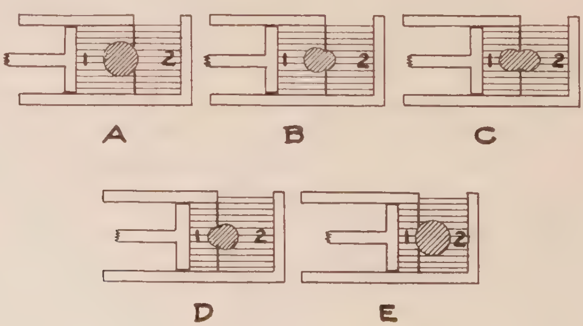

Fig. 3.

Suppose that we have a gas bubble of radius r_1 immersed in oil and approaching a capillary opening of radius r_2, as in Fig. 3*A*. Increase of pressure in cell 1 will bulge the bubble partly into cell 2. During this

process the relation $pr = 2T =$ a constant must hold; where r is the radius of curvature of the bulged surface. Continued increase of pressure in cell 1 will result in decrease of radius of curvature of the surface in cell 2, with consequent increase of pressure. This continues until the radius of curvature reaches a minimum (the radius of the hole, r_2) and the pressure a maximum (Fig. 3*B*). After this the radius of curvature must increase and the pressure decrease, and as this is accompanied by a decrease in radius of curvature of the part of the bubble left in cell 1, and a consequent increase in its pressure, the action takes place very rapidly. The bubble snaps through the opening, passes rapidly through the position of unstable equilibrium (Fig. 3*C*) and assumes the position in Fig. 3*D*.

Dodd mentions[10] the spasmodic motion of globules and bubbles in passing through sand interstices and ascribes it to surface tension. After the stage of Fig. 3*D* is reached, the bubble performs work in expanding to the position in Fig. 3*E*. The total mechanical energy, however, is not returned to the system; some of it is converted into heat, which may be conducted away.

The work required to deform the bubble to the position in Fig. 3*B* is

$$W = T\int_{S_1}^{S_2} ds = T(S_2 - S_1)$$

where S is the surface protruding through the opening at any instant and S_1 and S_2 are the protruding surfaces when the radii are r_1 and r_2, respectively.

If r_1 is much greater than r_2, the buoyancy of the protruding bubble will overcome the strength of the surface film ($2\pi r_2 T$) and it will pull loose, the remainder of the original bubble following in one or more segments.

Foams and Emulsions

As the writer has already pointed out[11] the gas bubbles liberated in the oil upon release of pressure may form a foam. A foam is a structure that requires special conditions for its formation and permanency. An impure substance, containing capillary-active and emulsifying constituents, and having low surface tension and high viscosity fulfills the requirements. The low surface tension is necessary for the very great development of surface presented by a foam[12] and, since the capillary-active constituents of an impure substance such as petroleum may concentrate in the surface films, this condition may be satisfied. Foam is

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[10] H. V. Dodd: Some preliminary Experiments on the Migration of Oil up Low-angle Dips. *Econ. Geol.* (1922) **17,** No. 4, 281, 288.

[11] F. G. Tickell: *Op. cit.*, 12.

[12] H. Freundlich: Colloid and Capillary Chemistry, 790. E. P. Dutton & Co., New York, 1926.

an unstable substance; special conditions are necessary for its formation but, these conditions being established, the foam may be extremely durable and permanent.

As stated above, the liquid lamellae separating the gas bubbles are extremely thin, and liquid drainage from the foam must be exceedingly slow, since it is at a rate proportional to the fourth power of the capillary radius. The writer has prepared petroleum-natural gas foams that were durable for long periods.

The same conditions that are favorable to the formation of foams are favorable to the formation of emulsions, except that (for the oil field emulsion) water forms the disperse phase. The viscosities of both foams and emulsions may be out of all proportion to the viscosities of their constituents until, as Bingham states[13] they may have the rigidity of solids. The resistance offered by an emulsion or foam is not the same phenomenon as is seen in the Jamin effect because the globules or bubbles, as the case may be, are often smaller than the capillary openings through which they pass and the bubbles themselves are not deformed to fit the opening. The bubbles of a foam may be extremely small and, since the excess of pressure in the bubble has been shown to be inversely proportional to its radius, the bubble may offer considerable resistance to pressure of solid bodies.

It appears from these considerations that pressure diminution in any part of a porous body containing oil and gas is accompanied by increase of effective viscosity, and it seems that where the propulsive force is decreasing and the resistance increasing, an equilibrium would be established rapidly. In addition to this, there is the pressure gradient extending upwards and outwards from the well, so that the pressure and resistance are different at all points within the drainage area. In the open type of reservoir, where edge water is entering at a rate insufficient for maintenance of pressure, there is the complication of this influence, which is itself a variable in terms of the variable reservoir pressure and the variable hydrostatic head.

Rate of Recovery

In the purely artesian type of reservoir, where there is no occluded gas in the oil, such as is found in some Mexican fields, rate of recovery (open flow) is either constant for a constant hydrostatic head or it is a simple function of time for diminishing head. If the reservoir is of uniform cross-section the flow will be a linear function of time.

In the closed type of reservoir the unrestricted rate of flow will depend upon whether there is initial pressure in the sand or simple gravity drainage. Gravity drainage will be similar to that of the artesian type

[13] E. C. Bingham: Fluidity and Plasticity, 1st ed., 211. McGraw-Hill Publishing Co., Inc., New York, 1922.

with diminishing head. If there is occluded gas the relation will be complicated because the effective viscosity will vary inversely with pressure and directly with proximity to the well. The experience of petroleum engineers has been that many production decline curves conform rather closely to the exponential or die-away type,[14] which may be expressed by the equation:

$$Q = a\epsilon^{-kt}$$

where Q = rate of flow (bbl. per day)
t = time elapsed (years)
ϵ = base of Naperian logarithms
a and k = constants.

This curve is a straight line on semilogarithmic paper, and as Marsh has pointed out,[15] its rate-cumulative curve is a straight line on rectangular paper. This is so because rate of flow (Q) is rate change of volume with respect to time, or

$$Q = \frac{-dV}{dt} = a\epsilon^{-kt}$$

$$-dV = a\epsilon^{-kt}\,dt$$

Then the cumulative volume lost by the reservoir:

$$-V = \int -dV = \int a\epsilon^{-kt}dt = \frac{a}{k}\epsilon^{-kt} + C$$

and, since both V and Q are exponential functions of time, the one is a linear function of the other.

Larkey obtained his data from reservoirs in the Mid-Continent field that are probably of the closed type, and finds that the simple exponential curve can be made to fit with considerable accuracy. This would seem to imply that a law similar to Newton's celebrated Law of Cooling Bodies would apply for these cases and that, at any instant, the rate of production is proportional to the amount of fluid remaining, or

$$\frac{-dV}{dt} = kV$$

The minus sign signifies that the volume decreases as the time increases. There seems to be no theoretical justification for the attempt to express the decline curve by an equation of the type $Q = a(t + k)^{-n}$ and to straighten and extrapolate it on double logarithmic paper.

Marsh obtained his data from California pools that are probably of the combined type and finds that, where production control remains constant, the rate-time curves follow the exponential law. Of course

[14] C. S. Larkey: Mathematical Determination of Production Decline Curves. *Min. & Met.* (1923) **4,** No. 199, 341.

[15] H. N. Marsh: New Method of Appraising Results of Production Control of Wells. *Natl. Petr. News* (1928) **20,** No. 24, 55.

that does not prove that if production control remained constant throughout the life of the well, the curve would follow a simple exponential or "compound discount" law, but it leads one to suspect that the average decline curve for a pool of this type is of some exponential type such as, for example:

$$Q = a\epsilon^{-(k_1t+k_2t^2)}$$

It will be difficult, if not impossible, to derive an equation of motion and time, or of motion and pressure, from theoretical and experimental considerations of the reservoir having, in a porous body, oil and gas under pressure, and either with or without a hydrostatic head. This is for the reason that the effective viscosity at any instant and place is a complicated function of the pressure, in which account must be taken of the surface tension, temperature, and possibly electrical and chemical effects. The experiment is on a scale too large and the facilities for making observations too limited.

Ultimate Recovery

The closed type reservoir should have the smallest recovery factor because there is no force (except gravity) to minimize capillary retention after gas pressure is depleted. The open type reservoirs will have recovery factors depending upon the foam-forming propensities of the oil and upon the amount of water in the hydrostatic column. It would seem that, in those cases where shutting in wells for considerable periods of time has resulted in increased recovery rate upon reopening, that the period of shutdown permitted the slowly infiltrating edge water to replenish the pressure.

In any type of reservoir, except the pure artesian, repressuring by gas injection should prove beneficial because the gas builds up a pressure that is more immediately available and quicker acting as a propulsive force against the oil, and because the increased pressure forces gas bubbles back into occlusion or solution in the oil and thereby reduces the effective viscosity of the fluid.

Gas bubble and foam resistance probably explains the difficulties that California operators have in injecting gas into some wells and the ease of injection into other contiguous and similar wells, *i. e.*, differences in production control, or other more obscure factors, have brought about greater viscosity in one well than in the other.

Conclusions

1. An oil and gas reservoir may be of the closed or open type. If of the open type, rate of flow may be a function of hydraulic flow alone or a continuous function of both hydraulic flow and release of gas pressure.

2. All influences in the reservoir that restrain the movement of fluids have the same effect as increasing the viscosity of the fluid. The presence

of gas bubbles (Jamin effect), water globules, emulsions and foams may all contribute to this effective increase of viscosity.

3. Release of pressure in a porous medium containing gas and oil is accompanied by increase of fluid viscosity, so that the less the propulsive force the greater the resistance to it.

4. The decline of production from the closed type of reservoir may usually be expressed as an exponential function of time.

5. The decline of production from the "combined" type of reservoir is a very complex function of time and has never been mathematically expressed.

6. Ultimate recovery from the closed or combined type of reservoir should be increased by repressuring methods.

7. Estimates of ultimate recovery, drainage areas, proper well spacing, etc., must be based on recognition of the combined type reservoir and the complex relations of its variables.

Appendix

Classification of Reservoir Systems

I. Closed Reservoirs

A. Production due to gravity drainage.
- 1. Reservoir rocks fractured or cavernous, but not porous.
  Little capillary retention of oil.
  Rate-time curve often lineal.
  High ultimate recovery.
- 2. Reservoir rocks porous.
  Considerable capillary retention of oil.
  Low ultimate recovery.
  Rate-time curve often lineal.

B. Production due to gas under pressure.
Pressure due to weight of superincumbent rocks or to increase of temperature after oil accumulation.
- 1. Reservoir rocks fractured or cavernous, but not porous.
  Gas will separate from oil and become entrapped or by-pass to the well.
  Gravity drainage will follow pressure decline.
  Rate-time curve often lineal.
  Fairly high ultimate recovery.
- 2. Reservoir rocks porous.
  Much gas may exist separately from and above the oil, but much will also remain occluded or dissolved in the oil while pressure remains constant.
  Pressure finds relief against an increasing fluid viscosity.
  Much capillary retention of oil and low ultimate recovery.
  Rate-time curve usually exponential.

II. Open Reservoirs

Hydrostatic column present.
- 1. No gas present (Artesian type).
  Production due to hydraulic flow.
  - *a.* Hydrostatic head is constant.

Production is constant.
Some capillary retention of oil.
High ultimate recovery.

b. Hydrostatic head diminishing.
Rate-time curve often lineal.
Ultimate recovery depends upon amount of edge water

2. Gas present.

a. Reservoir is not porous but consists of large fractures and voids.
Gas will separate from oil and become entrapped or by-pass to the well.

(1) Gas pressure release constantly and equally replenished by edge water encroachment.
Little capillary retention of oil.
Rate-time curve often constant or lineal.
High ultimate recovery.

(2) Gas pressure continually but not equally or constantly replenished by edge water encroachment.
Little capillary retention of oil.
Rate-time curve often exponential.
Ultimate recovery depends upon amount of edge water.

b. Porous reservoir.
Much gas may exist separately from and above the oil, but much will also remain occluded or dissolved in the oil while pressure remains constant.

(1) Gas pressure release constantly and equally replenished by edge water encroachment.
Pressure finds relief against a constant fluid viscosity.
Some capillary retention of oil.
Rate-time curve often lineal.
Ultimate recovery fairly high.

(2) Gas pressure release continually but not equally or constantly replenished by edge water encroachment (combined type).
Pressure finds relief against an increasing fluid viscosity.
Some capillary retention of oil.
Rate-time curve unknown but probably not a simple exponential.
Ultimate recovery depends upon amount of edge water.

DISCUSSION

J. O. Lewis,* Tulsa, Okla.—It would be impractical to discuss fully all phases of Mr. Tickell's paper which is predicated upon premises some of which, in the reviewer's opinion, are still unproven. The reviewer has therefore chosen to discuss one or two points only.

One of Mr. Tickell's conclusions is: "The decline of production from the enclosed type of reservoir may usually be expressed as an exponential function of time."

This mathematical expression of oil decline is an old one, having been used before 1910 in California and still earlier in Pennsylvania. This was the first type of curve used by the reviewer in California and in Oklahoma, and it was from noting the inadequacies of this type that he and others turned to the use of double-log paper. Since then the reviewer has been in continual search for evidence as to the graphical character of decline curves—to ascertain whether all declines followed one type, whether some followed the semilog type and others the double-log, or whether there

* Petroleum Engineer.

were still other types than these two. In this search many hundreds of production records have been analyzed including data from fields representing almost every condition that occurs in this country. Also evidence from experimental work and analogous engineering data has been considered.

The results of this search may be briefly stated. Never yet has the reviewer seen convincing evidence that the decline curve in a field where gas is the principal expellant is of the semilog type, and on the other hand he has never yet seen a long and regular curve from such a field that could not more satisfactorily be fitted to double-log paper than to any other.

The mass of data upon which this statement is founded cannot be presented here. The reviewer desires to direct attention to certain deceiving similarities between the two types of curves which he believes Larkey, Marsh, Tickell and others have not taken into sufficient account.

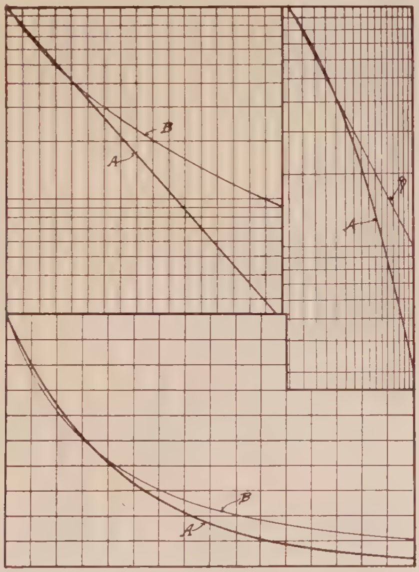

Fig. 4.—Two types of decline curves.

Curve A is a straight line on semilogarithmic paper. Curve B is a straight line on double logarithmic paper.

To illustrate the comparative natures of the two types of curves, the reviewer shows them on the three kinds of coordinate paper ordinarily used (Fig. 4); that is, arithmetical, semilogarithmic, and double logarithmic. Curve A is the exponential type which is a straight line on semilog paper and curve B is a straight line on double-log paper.

It will be observed that the two types follow each other so closely for the first six points that if plotting actual production records, the engineer could usually fit the points just as well to one as to the other. In some cases the irregularities in production would cause the points to fit one type best and in other instances, the other type. But if the next six points were available, the two curves deviate so widely that there would rarely be any question as to the fit except where major changes in operation methods had confused the record. It also is to be observed that the projection of the semilog curve will always give lower results.

Two curves were purposely selected for illustration that followed each other closely for some time. These are of the slowly declining type but the curves for wells of rapid decline deviate sharply and unmistakably in a much shorter time. It may be seen that from a practical standpoint the total error might not be important for slowly declining wells, though when used to measure the effect of a change in operating method over a term of years, the use of semilog paper may be very misleading. This seems to be the explanation for some of the findings on the favorable effects of vacuum for increasing oil recovery which differ widely from the findings of some other engineers.

The comparisons shown in Fig. 4 disclose the dangers of drawing conclusions from short and irregular records. It is only when the record has been plotted on both papers and shown to deviate definitely from one or the other trend that a conclusion is justifiable as to which it fits. The findings of Larkey,[16] are clearly vitiated because comparatively short records were used.

The reviewer's conclusions have been derived from his observation that every long and regular record from the type of field considered which he has had opportunity to analyze, fitted the double-log paper and could not be satisfactorily fitted to the semilog paper. The same is true for the few gas production curves available that produced over long periods at an approximately uniform percentage of their open flow.

A variant of the use of the exponential type of decline is to plot the cumulative productions against the current productions. This method has been used many years for gas by Mr. Leach of the Indian Territory Illuminating Oil Co. and by Earl Oliver for oil estimations.

It can readily be shown both by theory and by experience that when the cumulative gas production is plotted against the current open flow that the relation is not a straight line on arithmetical coordinate paper. Theoretically the relationship between cumulative production and rock pressure is a straight line and theoretically the other relationship cannot be. Practically the latter is almost always curved upward because the rock pressures reported are not the true average for the reservoir but represent the lowest pressures in the field which obviously are at the gas wells. This observational error causes an upward bend in the cumulative production-rock pressure curve and a downward bend in the cumulative production-open flow curve.

This method when applied to oil has the same practical utilities and limitations as does the exponential type of decline curve with which it relates. The reviewer realizes the practical utilities of the method which justifies its employment if confined within the limits of unimportant errors. It is also possible that the controlled production of California wells has a different type of curve than the free producing small wells and that during such conditions it does follow the exponential type. It would be profitable to study this relationship.

A few other points in Mr. Tickell's paper may be touched briefly. In discussing the source of the potential energy in gas, Mr. Tickell omits what in the reviewer's opinion is the most probable origin of gas pressure. That is the pressure generated when the gas was chemically derived from its parent solid or liquid state. The free gas will occupy over 1000 times the space of a solid, assuming the solid to have the specific gravity of water and this, unless inhibiting the chemical reactions, could generate a pressure over 10,000 lb. if the gas were confined to the space occupied by the parent solid.

The experiments of Power confirm experimentally Poiseuille's and Slichter's flow formulas for a liquid through a capillary body, though there appears to be a critical flow resistance. The case for the Jamin effect is not convincing. The experiments of the Bureau of Mines indicate that if a Jamin effect exists in the sense of building up a static back-pressure it must be very low under the conditions of their

[16] C. S. Larkey: *Op. cit.*

experiments, and the findings of Power are based on unsatisfactory evidence. The observations that shut-in wells regain production can, in the reviewer's opinion, be explained more satisfactorily by the building up of gas pressure around the well than by infiltrating edge water.

S. C. Herold,* Stanford University, Calif.—If Mr. Tickell wishes to solve his problem in terms of ultramicroscopic physics, that is, molecular physics, he no doubt will encounter complexities, inasmuch as he will at once make a necessary distinction between a liquid and a gas. Since we have never seen individual molecules of liquid and gas, we can be none too certain of the physical laws which we ascribe to them. I suggest that he give preference to the problem as it may be handled in molar physics. In this he would deal with masses of molecules—bubbles of gas and globules of oil, or larger quantities of both if desired. These quantities we readily see, measure, and watch in movement. Thus we may be perfectly certain of the laws which we ascribe to them. Complexities do not exist as before, for the molar physics or theoretical mechanics of liquids and gases are the same. No distinction need be made between them before the desired final interpretation of the data.

Mr. Tickell's apparatus is simply one in "volumetric control," typified by a solution tank (a reservoir of the open type) or by a rigidly constructed gas tank (a reservoir of the closed type). In a rigidly constructed gas tank he has placed both liquid and gas. The laws of production remain the same as in the tanks having liquid alone or gas alone. The data obtained by this apparatus will not be applicable to reservoirs in "capillary control" typified by the Jamin capillary tube. In other words, the data will be applicable to oil and gas reservoirs in California and in southern and west Texas, but it will not be applicable to oil and gas reservoirs in Kansas, Oklahoma, northern Texas, Wyoming, Ohio, Pennsylvania, New York, and so on.

W. V. Vietti,† Fort Worth, Texas.—Every well, depending on the sand and fluid conditions, will have a line with a definite slope—if the neighboring well has slightly different conditions, the slope of the production curve will be different. I am talking about one well and not the whole lease.

W. P. Haseman, Oklahoma City, Okla. (written discussion).—A straight forward and general solution of the problem of the flow of oil through a porous reservoir stratum to a well is possible provided the oil fluid mixture and the porous stratum fulfill certain requirements as to homogeneity and continuity during the time under consideration. The reservoir stratum is considered a charged capacity capable of dissipating its energy in the flow stream to the well as a place of low pressure. The dynamical condition to be fulfilled during the flow of the oil fluid mixture through the porous and permeable stratum into the well is expressed mathematically by

$$A\frac{d^2q}{dt^2} + B\frac{dq}{dt} + P = O \tag{1}$$

Equation 1 is general in its application and states that the acting pressure P, which causes the flow of the oil mixture through a section of the stratum, is equal in magnitude and oppositely directed to the algebraic sum of two reacting forces which oppose the flow, namely, the force $B\frac{dq}{dt}$ due to factors of the nature of viscosity, and the force $A\frac{d^2q}{dt^2}$ due to factors of the nature of inertia arising from a mass of oil approaching the well radially with an increasing velocity. A and B are operational factors

* Petroleum Geologist.

† Production Engineer, Marland Oil Co. of Texas.

for a given well dependent upon the physical characteristics of the producing stratum and its contained fluids. These factors, in general, do not remain constant with time for a producing well, however much knowledge can be secured about them from the producing characteristics of the well.

With A and B considered as constants for the period of time under consideration a solution of equation 1 may be had for assumed values of the acting pressure P. For example,

$$q_t = Ae^{-\alpha t} \tag{2}$$

satisfies equation 1 when P equals zero and is therefore a solution of the equation under that condition. This solution satisfies the initial and final conditions of a producing well. Similarly it is easily deduced from the above equations that

$$Q_t = Cq_t + Q_0 \tag{3}$$

where

1. A, C and α are operational constants dependent upon the producing characteristics of the well and producing stratum.
2. t is time in some time unit.
3. q_t is interval production in barrels during tth interval.
4. Q_t is cumulative production in barrels during the tth intervals.
5. Q_0 is the ultimate production in barrels.

Thus we have a theoretical basis for the reported linear relation between interval production and cumulative production. A detailed theoretical study of the more general cases of this problem reveals that an application of the fundamental laws of mechanics to the flow of fluids to and from a well yields information which can be used as an economic guide to the rate of flow of oil from a well, and the ultimate production of wells with pressure control methods. To my knowledge this derived linear relation between interval production and cumulative production has been in use since 1923 by a number of geologists and engineers in the estimation of oil reserves from producing properties.

Much study and experimental work have been and are being done on the molecular properties and phenomena of fluids contained in and flowing through a porous and permeable earth stratum with pore openings of capillary size. These studies have been on films, capillary phenomena, porosity, sand texture, etc. It would appear that the economic importance of such studies rests more with the production of oil from sands that have been mined rather than from sands through wells.

W. V. Vietti.—How many wells seemed to have homogeneous sand conditions?

W. P. Haseman.—Very few, but as soon as they happen to deviate from the production line I know what to do with them.

W. V. Vietti.—Is there any difference in the way a pure gas-drive sand will act and a pure water-drive sand will act? Do you get a very sudden break in curves when the water drive becomes predominant.

W. P. Haseman.—Yes.

L. C. Uren,* Berkeley, Calif. (written discussion).—This paper will not only be helpful to many in developing a clearer conception of the physical laws governing expulsion of oil from the reservoir sands, but in addition, presents a number of well founded theories and conclusions that will be new to most readers.

If anything need be added to Professor Tickell's analysis, the writer would urge that more emphasis might be placed on the influence of gravitational segregation of gas and oil within the oil sand. An oil sand is not exactly a "bundle of capillary

* Professor of Petroleum Engineering, University of California.

tubes" converging on a well as one writer has assumed, but, if the capillary channel concept is to be retained, is rather, a bundle of capillary tubes of varying size and with perforated sides, so that each capillary channel communicates with its neighbors. It seems doubtful under such circumstances, if we could expect conditions entirely analogous to those existing in separate capillary or Jamin tubes. The so-called "Jamin action" characteristic of gas and oil movement through sands, is not confined to channels paralleling the bedding planes, but is of such character as to afford ready vertical segregation of the gas and oil. In this, gravity plays an important role. In the early stages of gas expansion when the gas bubbles are small, they may pass through the sand pores with but little if any distortion; and due to their lower density and the buoyant force of the oil in which they are immersed, they tend to move upward through the sand pores rather than along horizontal flow channels. This results in rapid concentration of gas toward the upper horizons of the bed in which it and the oil are confined.

Relatively large bodies of free gas thus segregated from the oil, may exist in the form of a froth as Professor Tickell suggests. Whether or not these gas-oil froths are permanent in the sense that their enclosing oil films persist over long periods of time, is, however, open to question. While they may approach the rigidity of solids when totally confined, the individual bubbles and their separating films are susceptible of readjustments in position relative to each other with small energy consumption. The writer prefers to think of these froths as offering comparatively little resistance to displacement and believes that in most cases the enclosing films show a distinct tendency to coalesce, permitting the gas to move with comparatively little resistance to the outlet wells.

Trapped bodies of free gas above the general oil surface, on the other hand, may exert important static pressures forcing horizontal movement of oil through the sands. In thick or steeply inclined oil sands, gravity alone may develop a considerable horizontal component tending to cause movement of the rock fluids. Gravitational effects may thus either directly or indirectly result in the development of expulsive pressure on the oil, comparable in magnitude in some instances with that of expanding gas occluded within the oil.

There are at least five different sources of expulsive pressure that may be operative in expelling petroleum from its reservoir sands, each producing its own peculiar effects and following its own natural laws in reaching equilibrium with the retentive forces. These are: (1) the pressure exerted by expanding bubbles of gas occluded within the main body of the oil; (2) pressure exerted above or behind concentrations of oil due to trapped bodies of free formational gas; (3) fluid pressure due to the horizontal component of gravitational attraction on the oil; (4) edge-water pressure, and (5) fluid pressure developed by compaction of the reservoir sand and consequent shrinkage of pore space resulting from release of gas pressure. The latter is probably a force of no very great magnitude in most cases. The writer believes that any or all of these forces may be simultaneously operative, and agrees with Professor Tickell in his statement that they would be very difficult if not impossible to express in any mathematical relationship. It would seem, furthermore, that structural and lithologic irregularities would preclude the use of the mathematical method of analysis in any practical evaluation of the expulsive effect due to the combined action of these forces.

Mathematical analysis is further complicated by the fact that the pressure gradient from the wall of a well to the perimeter of its drainage area is not a straight line, but one which normally results in most of the pressure loss occurring within a comparatively short distance of the well. The writer has previously pointed out[17] that due to

[17] L. C. Uren: Increasing the Production of Petroleum by Increasing the Diameter of Wells. *Trans.* A. I. M. E. (1925) **71,** 1276.

the radial characteristics of flow toward a well, the velocity of flow rapidly increases as the wall of the well is approached, and that in a typical case of a well draining an area 600 ft. in dia., more than half of the pressure loss occurs within 10 ft. of the walls of the well. If this be true, it follows that the rate of growth in size of gas bubbles and rate of increase in viscosity and other related phenomena are of particular significance in the vicinity of the well, for unfortunately this zone is the critical one through which all of the oil produced must pass.

F. G. TICKELL (written discussion).—The writer has been thinking principally of decline curves of individual wells. He objects on theoretical grounds to decline-curve fitting by the hyperbolic law. The curve is asymptotic to both coordinates, whereas some exponential types, such as

$$Q = \partial e^{-kt} - e^{-k^1t} \qquad [1]$$

can be made to fit the whole curve rather than a part of it; for in this equation, $Q = 0$ when $t = 0$; Q increases to a maximum as the well is opened up and then declines asymptotically to the time axis.

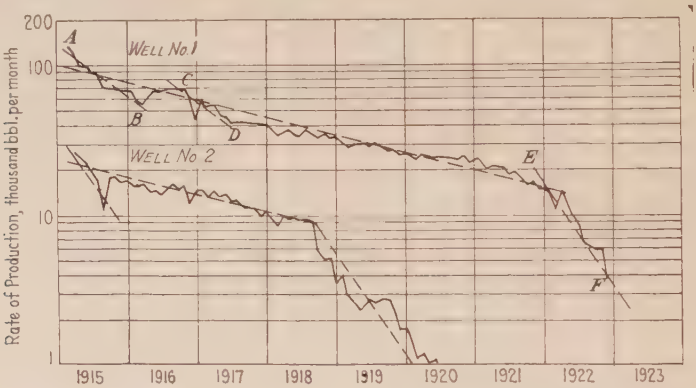

FIG. 5.—PRODUCTION CURVES OF TWO FLOWING WELLS IN SUNSET-MIDWAY FIELD.

If one may ignore the accelerating production part of a curve, the right-hand term of equation 1 may be eliminated, giving thereby the simple exponential, which is linear on semilog paper.

From the practical standpoint, the double log plotting is convenient, but so also is the semilog plotting, and the latter has the added advantage of giving a linear rate-cumulative curve on rectangular coordinates. In the no doubt numerous cases of average decline curves that will not follow the simplest form of the exponential law, but which seem to be fit by the hyperbola, the use of the latter is convenient. One might also follow the common procedure of the physical chemist in using an equation of the polynomial type, with which the perfection of fit depends only on the number of terms used, but this would involve use of the equation for extrapolation.

Recently, interest in California has been centered on the decline curves of individual wells and the application of the exponential law has been made by Marsh and others for the purpose of predicting production trends as affected by cperating methods.

The curves of Fig. 5 are submitted as interesting examples of contiguous flowing wells which produced under similar and uniform conditions. That is, there was no change of back-pressure during the period of flow. The curves show two distinct trends of production, the flexure occurring in each case at approximately the same production rate (10,000 bbl. per month).

In Fig. 6, the rate-cumulative curve is given for well No. 1. From this curve, it appears that one trend of production is repeated three times (*A-B*, *C-D*, *E-F*) with

a different trend (D-E) between. Well No. 2 exhibits somewhat parallel trends. The double log plotting does not bring out these trends. The trend E-F is not emphasized on the rate-cumulative curve and, on the other hand, the trends A-B and C-D are not clear on the semilog curve. Both curves are necessary to demonstrate the well's behavior.

Since the author has not discussed molecules, nor entities smaller than bubbles of gas and oil, he suspects that Mr. Herold would wish us to confine ourselves to still greater things. Barrels of oil per day, casing and tubing head pressures—these things certainly are "macroscopic" enough; yet we have not been entirely successful, somehow, in divining from them the "intrinsic harmony" they are supposed to disclose. The writer feels that perhaps it might help to supplement the evidence furnished by these greater things by evidence furnished through the behavior of the smaller things that called them into being. He thinks that we might even, with

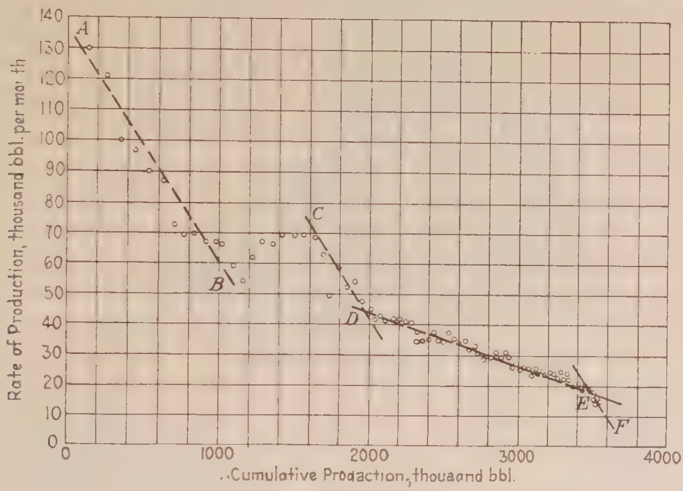

Fig. 6.—Rate-cumulative curve of well No. 1.

profit, investigate the lowly molecule and perchance deduce from its attributes the laws of gas diffusion in oil-wet sands or of other phenomena that might have a bearing on repressuring or the like.

The writer wishes to point out what Mr. Haseman would no doubt admit—that his equation 1 is applicable only in a generalized sense. It seems impossible to express what happens in an oil sand by a differential equation involving time only. The conditions are analogous to those involving the flow of heat, and the like, in which spatial as well as temporal considerations are involved. In addition to this, A, B, and P cannot be expected to remain constant, and for these reasons the decline function is probably more complicated than the simple exponential of his equation 2. Mr. Haseman's reasoning, however, gives support to the idea that the simple exponential is the best first approximation.

The writer agrees with Professor Uren that attention should be paid to the influence of gravitation on segregation of gas and oil within the reservoir. He wishes also to offer the suggestion that possibly we are not justified in assuming isothermal conditions during oil and gas movement to the well. If the conditions approach the adiabatic, the fluid would gain effective viscosity, because of loss of gas from the oil and bubble resistance, but would lose viscosity on account of increase of temperature.

Natural-flow and Gas-lift Experiments and Apparatus*

By R. R. Brandenthaler,† G. Wade‡ and W. S. Morris,§ Bartlesville, Okla.

(New York Meeting, February, 1929)

Petroleum engineers generally are of the opinion that the flow conditions and, therefore, the formulas that apply to the flow of oil and gas in long pipe lines differ in many ways from flow conditions in oil wells. One of the reasons why the formulas in common use for pipe-line flow do not correctly apply to oil wells is that the flow lines are vertical and not horizontal. Another factor to be considered is that the fluid is a mixture of oil and gas and that the physical characteristics of these two components are affected differently by changing conditions of pressure and temperature during upward flow.

Realizing the need for accurate data on flow in vertical pipes under conditions caused both by natural flow and the gas-lift, the U. S. Bureau of Mines has installed equipment at the Petroleum Experiment Station, Bartlesville, Okla., for the purpose of studying this problem. In addition a study will be made of the comparative effects of different natural-flow and gas-lift methods of producing oil on ultimate production from reservoir sands.

Experimental Equipment

The experimental equipment consists of a regular oil-field steel derrick, a large pressure tank installed in a concrete pit beneath the derrick floor, compressors and pumps, gas separators and absorbers, metering and control devices, and the necessary pipe connections. The crown-block level represents the derrick floor at an oil well, and the "producing sand" is the pressure tank below the derrick floor. The difference in elevation between the crown-block level and the tank is 90 ft. Figs. 1, 2 and 3 show the construction and exterior arrangement of the equipment.

The success of the experiment will of course depend largely upon the accuracy of the oil and gas measurements and the temperature and pressure determinations. Because extreme accuracy is necessary, all oil and gas measurements will be checked at least twice, and in some

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* Presented by permission of the Director, U. S. Bureau of Mines.

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cases three times. Many problems have been encountered in selecting proper equipment, but these will not be discussed in this paper.

FIG. 1.—CONSTRUCTION OF DERRICK AND ARRANGEMENT OF EQUIPMENT IN DERRICK.

FIG. 2.—VIEW OF COMPLETED DERRICK AND EXTERIOR EQUIPMENT.

FIG. 3.—VIEW OF DERRICK AND EXTERIOR EQUIPMENT.

Information Desired

The information desired is the velocity of flow and the density of the fluid at various points in the flow line, the volume of free gas and gas in

solution in the oil, the pressure and temperature of the fluid at different levels in the tubing or casing, the rate at which gas and oil are produced, and the pressure and temperature drop across the face of the sand. From this information it is hoped to develop fundamental laws of flow of oil-gas mixtures in vertical pipes, and to obtain comparisons between the changes in flowing conditions which are produced by varying the size of flow lines and the pressure and temperature in the sand reservoir and flow lines.

Sand Reservoir

A considerable amount of thought was given to the selection of a sand reservoir that would be best suited for the purpose of the investigations. It was recognized at the outset that an upright cylindrical tank

FIG. 4.—RESERVOIR TANK.

to permit radial migration of the oil was most desirable, but a reservoir of such design was not installed for the following reasons: (1) the available space under the derrick floor was limited and could not be increased except at a great cost; and (2) the cost of constructing an upright cylindrical tank of the size desired and for the pressure necessary was too great.

The tank shown in Fig. 4 was finally decided upon mainly because it could be purchased, completely equipped with manholes and other openings, and installed in the available space below the derrick at a nominal cost and without great difficulty. The tank is 6 ft. dia. and

64 ft. long, all seams and rivets are electrically welded, and the bursting strength is calculated to be 740 lb. per sq. in. The tank was subjected to a hydraulic-pressure test of 300 lb. per sq. in.; as it will be operated at a maximum working pressure of only 200 lb. per sq. in. the safety factor is considered ample.

Sixty 3-in. collars are equally spaced and welded into the side of the shell 2 ft. from the bottom. Perforated pipes, "injection tubes," each 5 ft. 5 in. long and extending into the tank, are screwed into special bushings which in turn are screwed into the 3-in. collars. If any of the perforated pipes should become inoperative, they may be removed by

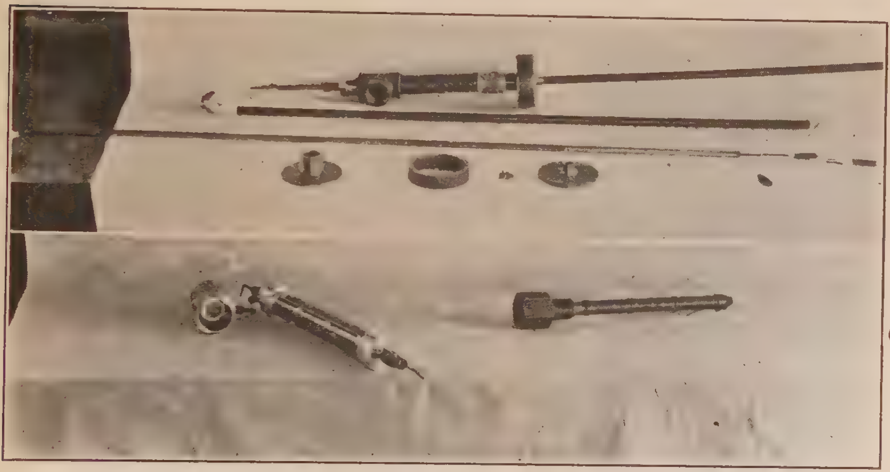

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Fig. 5.—Reservoir temperature and pressure devices, and subordinate well screens.
Fig. 6.—Reservoir end wells, thief and fluid sampler.

revolving the tank 45°. The concrete pit is so constructed as to allow changing the position of the tank.

Each of the 3-in. collars is connected by 1-in. fittings to a 3-in. manifold. The flow of oil or gas may be divided into any desired combination of injection tubes by means of plug-type valves in the 1-in. fittings. Needle valves permit the taking of samples from the injection tubes.

Three 4-in. collars are welded into the top of the tank; these are "producing well" openings. The center well is located under the center of the derrick. The other two are at equal distances from the center 4-in. collar and near the ends of the tank.

Seventeen 1-in. collars, spaced at regular intervals, are welded into the tank along the top. These are "subordinate wells" and provide a means of observing pressures and temperatures. Fig. 5 shows clearly the construction of the temperature and pressure elements and the subordinate well screens; a detailed description of them is therefore

unnecessary. Two 1-in. collars are welded into the tank adjacent to each of the three main producing wells, and provide means for obtaining the pressure and temperature in the well and in the sand immediately adjacent to the well.

Three 1-in. collars are welded into each end of the tank in the same horizontal plane as the sixty 3-in. collars. These are equipped so that they may be used for charging the reservoir with either gas or oil; they may also be used as oil and gas outlets. Their construction is shown in Fig. 6.

Each of the three producing wells is provided with 3-in. perforated pipe which extends from the 4-in. collar to within 6 in. of the bottom of the sand in the tank (Fig. 7).

Eight manholes along the top provide openings for charging and packing the reservoir with clay and sand. The manholes are also used when installing injection tubes (Fig. 7), pressure and temperature devices (Fig. 5), perforated pipe for producing wells (Fig. 6), and metal inflation chambers for packing the sand (Fig. 8).

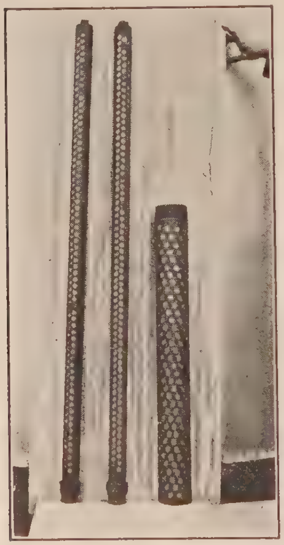


FIG. 7.—PRODUCING WELL SCREEN PIPE, AND INJECTION TUBES.

FIG. 8.—METAL DIAPHRAGMS; PRESSURE CHAMBERS.

The reservoir has been packed to a height of 2 ft. with clay. Grooves for the 2-in. dia. injection tubes are provided along the top of the clay. Each injection tube is perforated halfway around the circumference but the other lower half is blank and rests in the grooves.

The clay forms a more or less rigid mass in the tank, and as the tank will expand slightly when subjected to pressure it was thought necessary to provide against possible by-passing of oil or gas from the sand into the space between the shell of the tank and the clay. To prevent by-passing of oil or gas into this space a "flashing" consisting of 22-gage black iron has been electrically welded to the inside walls of the tank,

extending approximately 12 in. into the clay. Preliminary tests showed that any gas or oil which might by-pass was forced to travel along the upper surface, around the edge, and along the under side of the iron flashing. Since the clay is packed tightly against the upper and lower surface of the flashing, any by-passing which might occur would be small and relatively unimportant.

After the various screened wells, recording instruments, and other devices are installed in the tank, Wilcox sand will be packed to the greatest possible density to within 6 in. of the top. Twenty metal inflation chambers (Fig. 8) will then be placed in a horizontal position on the sand, and additional sand packed on top to fill completely the reservoir. The inflation chambers are manifolded in groups within the tank by copper tubing and are connected to outlet fittings in the manhole covers. The outlets through the manhole covers are connected to an exterior manifold. Pressure will be applied to the inflation chambers to further compress the sand. The pressure will then be released, additional sand placed in the reservoir, and pressure reapplied. To reduce the tendency of oil and gas to by-pass between the walls of the reservoir and the sand, pressure will be maintained in the inflation chambers in excess of the tank pressure throughout the experiments. As a precaution against further by-passing of oil and gas a coat of shellac will be applied to the inner wall of the tank above the clay and also to the metal inflation chambers and copper tubing; sand will be sprinkled on the shellac while it is still liquid.

Fig. 9.—Absorber.

Absorber

The absorber (Fig. 9) is 24 in. in dia. and $26\frac{1}{2}$ ft. high; it is to be used for dissolving the gas in crude oil at the desired pressure. It is equipped with 10 trays and a mist extractor. The mist extractor will strip oil from the excess gas which leaves the section of the absorber above the top tray. A back-pressure regulator will control the pressure in the absorber, and the desired oil level will be maintained with a liquid level control. Excess gas will leave the absorber at the top, pass through the back-pressure regulator and drip, to a meter.

The rated capacity of the absorber is 40 gal. of oil per min. at 250 lb. pressure.

Tubing and Casing

After investigating various kinds of tubing, it was finally decided to use an aluminum alloy tubing. Its chief advantages are: close tolerance of internal and external diameters; very smooth inner wall, thus reducing variations in wall friction in the same diameter pipe to a minimum; extreme lightness; and ease of machining. In addition it can be purchased at a reasonable cost.

It is planned to use various sizes of tubing and casing, ranging from $1\frac{1}{4}$ to 3-in. internal diameter, which will permit a wide range of tubing and casing combinations.

FIG. 10.—LOOK-BOX, THIEF AND TUBING.

Flow lines consist of 9-ft. lengths of tubing and casing and 12-in. look-boxes. It was necessary to construct the thief sections of the look-boxes for each combination of tubing and casing because of the position and length of the sampling thief (Fig. 10).

DISCUSSION OF APPARATUS

As accurate measurements are essential, a considerable amount of time has been devoted to a study of the various measuring and metering instruments. Because of constantly changing conditions during the experimental runs and because of the number of observers that would otherwise be needed, recording instruments have been adopted for use wherever possible. To give some idea of the data required, provision has been made for obtaining pressure readings at approximately 70 points, and temperature readings at approximately 90 points. Provision has also been made to measure gas volumes at 14 points and oil volumes at 9 points. In addition, measurements of oil and gas will be obtained with the samplers at each 10-ft. interval in the flow line.

Recording differential and static pressure gages, test spring gages, and dead-weight testers will be used for obtaining pressures. Recording differential pressure gages will be used to obtain the differential pressures between 10-ft. sections in the flow line; between the well and the sand immediately adjacent to the well, and between points in the sand uniformly spaced between the center well and the ends of the tank. Pressures in other parts of the system will be obtained with spring test gages.

Thermocouples, by which temperatures can be determined to within 0.20° F. will be used. A new type of potentiometer which is especially rapid in its action will be used in conjunction with these thermocouples. Three potentiometers will serve to obtain temperatures at the numerous thermocouples throughout the entire system.

Temperature lag has been given serious consideration and the designing of apparatus to reduce the lag to a minimum has required much study. A detailed view of the devices for obtaining both temperature and pressure in the sand reservoir is shown in Fig. 5. The thermocouples are in direct contact with the oil, and any change in the temperature of the oil becomes apparent immediately.

In the oil fields, ground temperatures decrease from the bottom of wells to the surface. To simulate these conditions, two suction fans, installed on the derrick floor, draw the cooler air in through a revolving ventilator at the top of the derrick, cause a downward flow, and expel the warmer air through openings at each end of the reservoir house.

Ten displacement-type gas meters each equipped with special castor oil diaphragms, volume and pressure recording gage, and 3-hr. clock, will be used for measuring gas volumes. These meters measure gas volumes accurately to within 1 per cent. The meters are connected so that they can be easily and accurately checked with a critical flow prover. Greater accuracy than 1 per cent. can be obtained, therefore, by calibrating the meters with the prover and applying corrections. It is planned to check all meters before starting each run. To serve as an additional check, an orifice meter has been installed ahead of the intake master meter.

The oil will be measured with a displacement-type oil meter equipped with a gas eliminator, sediment trap and thermostat. Calibrated gaging tanks will also be used.

Look-box and Fluid Sampler

For the purpose of sampling the fluid flowing from the reservoir to the top of the derrick, look-boxes equipped with a thief will be installed at 10-ft. intervals in the flow line. Temperatures and pressures will also be obtained at each look-box. The design of the look-box is shown in Fig. 10.

The sampler used in conjunction with the thief is shown in Fig. 6. Each sampler is constructed of aluminum tubing containing a section of pyralin tubing which is graduated so that volumes, either oil or gas, can be determined by visual inspection. It is planned that as soon as samples are obtained, temperatures will be observed and the samples placed in thermos containers to prevent temperature changes. The containers will then be placed in a centrifuge and revolved at a predetermined rate to separate the free gas and oil. The volume of free gas will

be determined readily by referring to the scale on the sampler. The sampler will then be weighed to determine the density of the fluid. The quantity of free gas and gas dissolved in the oil will be measured by the water displacement method at atmospheric pressure.

Gravity balances will be used to determine the gravity of the gas at the entrance of the system and at other strategic points. Gas analyses will also be made during the experiments in order to study the effect of selective solubility in the absorber, and changes in the gas in other parts of the system. Changes in the gravity and character of the oil will also be determined during the progress of the experiments.

Cycle of Operation

Figs. 11, 12 and 13 show the cycle of operation. Natural gas will enter the system from the city main, pass through a drip, and then through an orifice meter. From the orifice meter it will pass through a dust collector and through the master meter into a low-pressure header. This header serves for both the charging cycle and gas-lift input system; it also redistributes gas returned from the sand reservoir, separators and absorber.

In charging operations, gas will be withdrawn from the low-pressure header through a meter into the high-pressure compressor. There it will be compressed to pressures between 200 and 250 lb. and then discharged through a cooling or heating system into a high-pressure receiver. Gas from this receiver will pass through a regulator and meter into the bottom of the absorber at a pressure of more than 200 pounds.

Sufficient crude oil for the first run will be drawn from the main storage tank through an oil meter and distributing manifold and thence pumped by a triplex pump into an intermediate storage tank. Later, the oil for the first run will be withdrawn through the distributing manifold and oil meter and pumped into the absorber immediately above the upper tray.

Excess gas in the absorber will pass through the mist extractor at the top into a drip, through a meter, and back to the first low-pressure header, before being taken back into the circulating system; or it may be allowed to escape to the atmosphere after leaving the meter. Various methods are provided for charging the reservoir with oil and gas. In one method the reservoir will be charged with gas at a pressure of 200 lb. per sq. in. Then the gas-saturated oil from the absorber will pass through the 3-in. charging header into the 60 injection tubes, from which it will be forced into the sand at a low differential pressure.

As the oil enters the sand, some additional gas probably will be absorbed by the oil. Excess gas will be forced from the reservoir into a gas manifold through the screened subordinate wells, which are arranged along the top of the tank. Pressure in the sand will be maintained at

FIG. 11.—PHOTOGRAPHIC FLOW SHEET

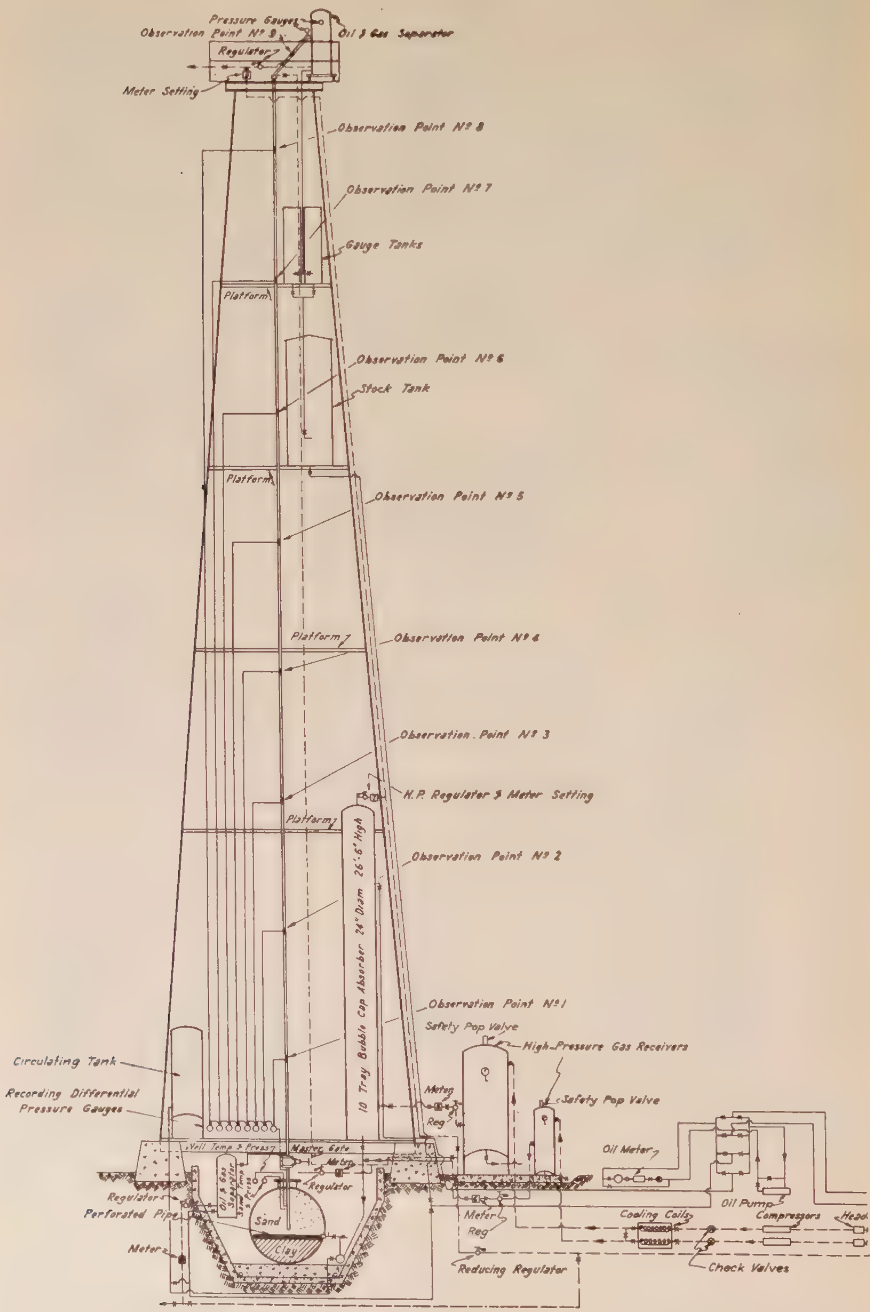
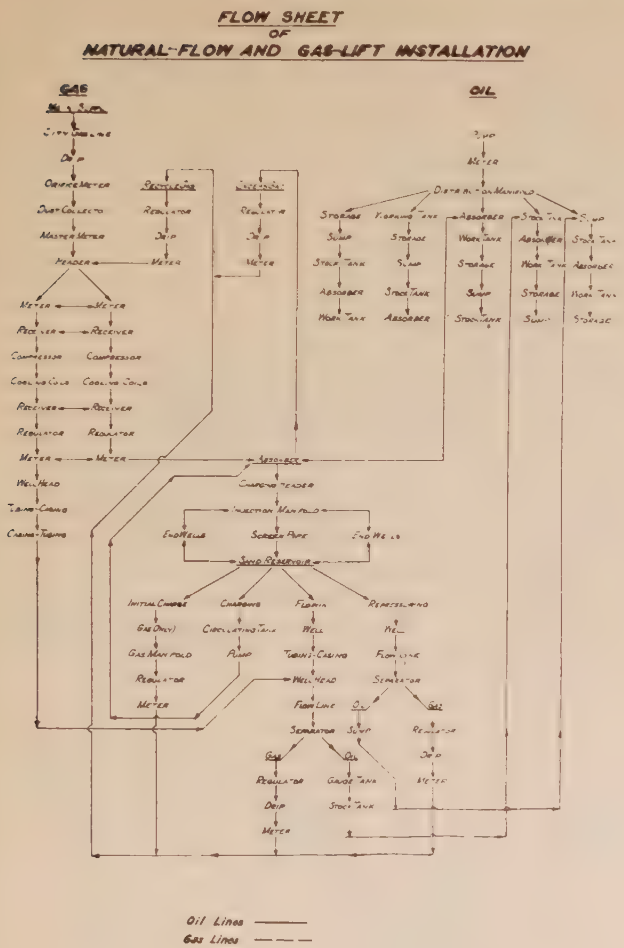
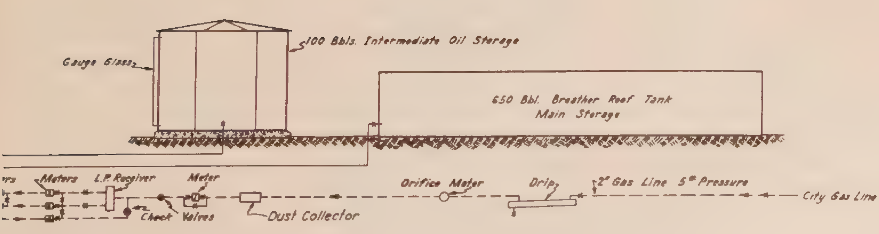


FIG. 12.—DIAGRAMMATIC





ELEVATION AND FLOW SHEET.

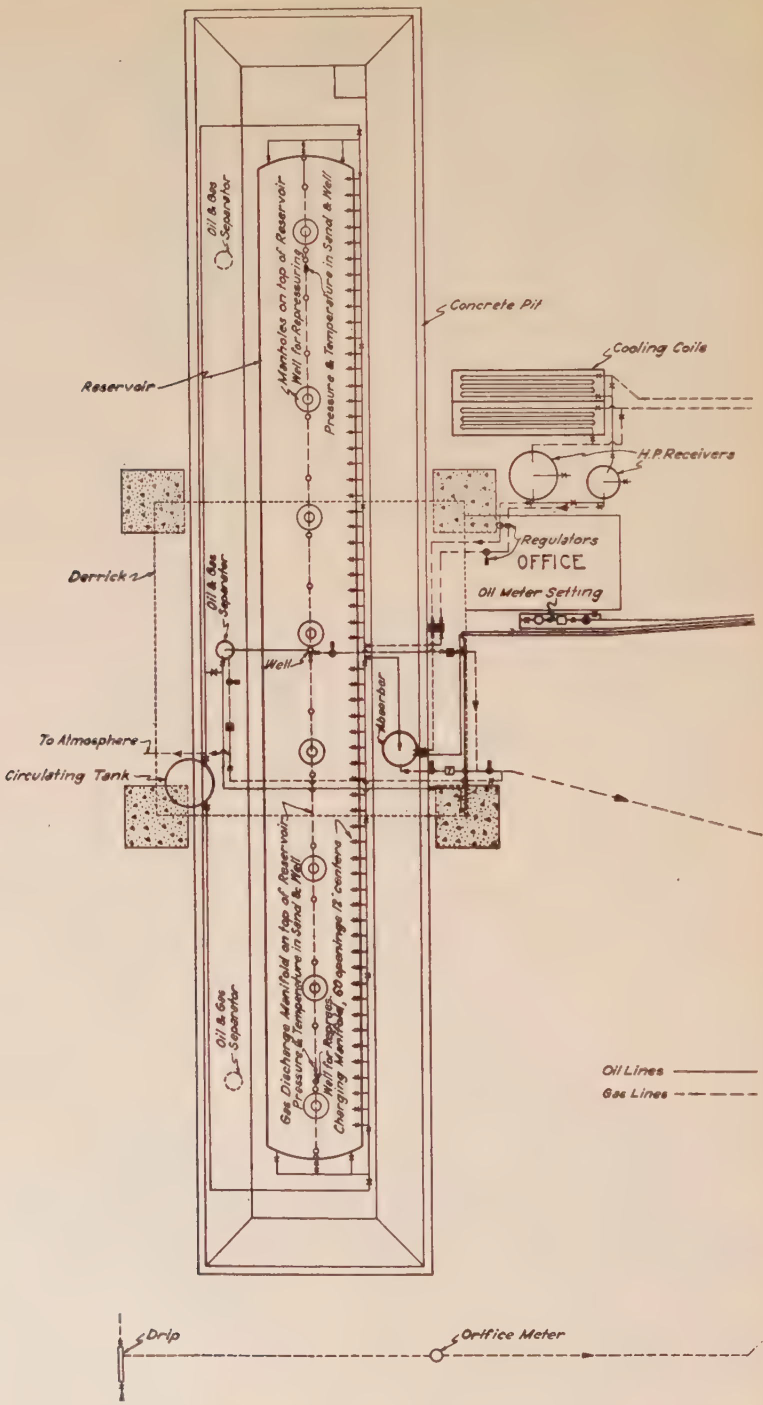
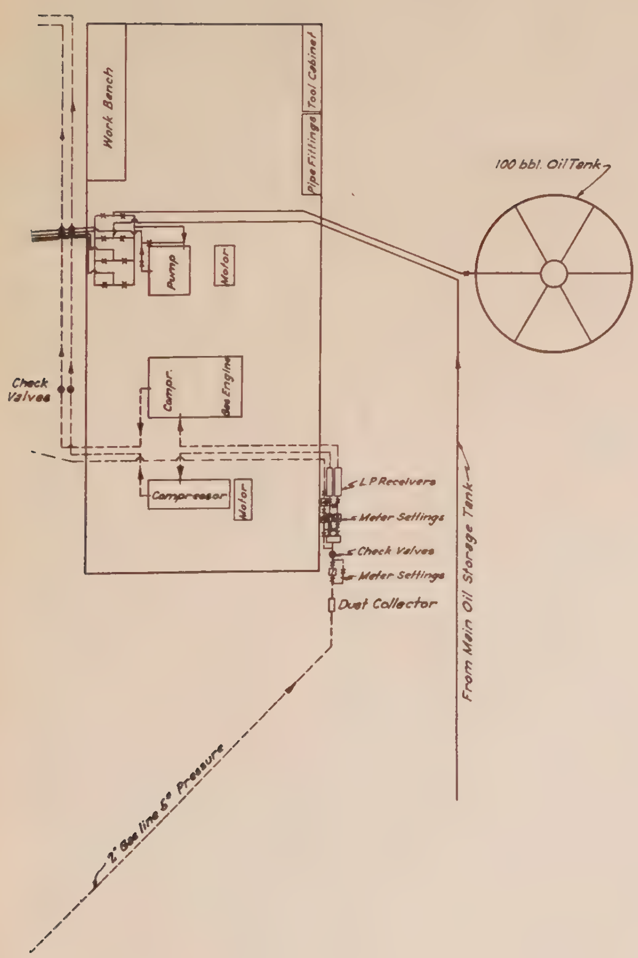


FIG. 13.—DIAGRAMMATIC


Work Bench
Tool Cabinet
Pipe Fittings
100 bbl. Oil Tank
Pump
Motor
Compr.
Gas Engine
Check Valves
Compressor
Motor
L P Receivers
Meter Settings
Check Valves
Meter Settings
Dust Collector
From Main Oil Storage Tank
2" Gas line 5# Pressure

PLAN VIEW.

200 lb. per sq. in. by means of a back-pressure regulator installed on the gas manifold. From the manifold the gas will pass through a drip and meter into the first low-pressure header before again entering the circulating system; or after being metered it may be discharged to the air.

As soon as the reservoir is completely charged, which will be indicated by the volume of oil injected and by close observation of transparent sections in the 1-in. lines leading from the subordinate wells to the gas manifold, charging operations will be discontinued and all valves on the reservoir closed.

The center well in the tank into which tubing or casing, or both, have been inserted, will be opened and the well allowed to produce to the well head on the crown-block line of the derrick. Thieves inserted every 10 ft. in the flow line will provide a means of obtaining fluid samples, which will be taken at definite time intervals. Pressure and temperature readings also will be taken at the same points where the thieved samples are obtained. The fluid from the well head at the top of the derrick will be discharged into an oil and gas separator. Oil from the separator will be discharged into gage tanks where it will be measured, and then into the flow tank where it will be measured again. From the flow tank the oil will return through the oil meter and pump to the intermediate storage tank for reconditioning.

Gas from the separator will pass through a drip and meter and then will either be discharged to the atmosphere or returned to the first low-pressure header for further use.

As soon as natural flow ceases, gas-lift methods of production will be applied to the "well." It was pointed out previously that gas from the first low-pressure header will be used either for charging the reservoir or for gas-lift operations. When producing the well by the gas-lift, gas will be withdrawn from the header through a meter into another low-pressure header to a compressor where it will be raised to the desired pressure. The gas passes from the compressor through a cooling or heating system into a high-pressure receiver, then through a regulator and meter into a vertical gas line leading to the well head. At the well head the gas will be injected either into the tubing or between the tubing and casing, as desired. The gas-lift method of flow will be continued until the reservoir pressure has declined to the stage where the lift becomes inoperative under ordinary or special methods of operation. Before recharging the reservoir for the next experiment, the sand in the reservoir will have to be depleted further of its oil to a definite minimum saturation which will be established for all tests. To remove the oil, gas will be injected into the reservoir through any one or several of the openings in the tank.

Other Methods of Charging Reservoir

Assuming that the method described for charging the reservoir with oil and gas is not satisfactory, means are provided for circulating oil through the reservoir until the desired reservoir conditions are obtained. This may be accomplished in a number of ways because the charging system is flexible and many combinations of flow through the reservoir or cycles are possible. For example, gas-saturated oil from the absorber may be charged into the reservoir through a group of injection tubes at one end of the tank and withdrawn from a group of injection tubes at the other end and discharged into a circulating tank on the derrick floor. The oil may be drawn by the triplex oil pump through the oil meter and pumped back into the absorber. From the absorber it may again be returned to the reservoir as described under "Cycle of Operation," thus making recycling possible. "Make-up" oil and gas can be taken into the system if required.

Another method of charging the reservoir would be to inject the oil into the sand through the 60 injection tubes and allow it to discharge through the 17 subordinate wells along the top of the tank into the circulating tank on the derrick floor. The cycle is then complete as in the preceding method.

Pertinent Facts Regarding Experimental Equipment and Proposed Tests

The reservoir when completely charged with sand and clay, will contain approximately 503 cu. ft. of clay and 1250 cu. ft. of sand. It has been estimated that the porosity of the packed sand will be approximately 30 to 35 per cent. On that basis, about 75 bbl. of crude oil will be required to fill the voids in the sand.

Although no solubility tests have been made on the oil that is to be used in the experiments, it has been estimated that 3500 to 4000 cu. ft. of gas or approximately 45 to 55 cu. ft. of gas per bbl. of oil will be required to saturate the oil at the desired pressure and temperature. For safety reasons the maximum reservoir pressure for all tests has been established at 200 lb. per sq. in. The absorber, however, will have to be operated at a pressure in excess of 200 lb. to provide for the movement of oil into the sand.

The ideal pressure for charging the sand in the reservoir with gas-saturated oil would be that which gave the lowest differential pressure at the face of the sand in the injection tubes. However, such a differential pressure would be prohibitive in these experiments because of the length of time which would be required to charge the sand. In order to reduce the charging time between tests it is expedient to inject the gas-saturated oil at a fairly rapid rate and at a low differential pressure.

Accordingly, the charging equipment was designed with this objective in view. The 60 injection tubes provide approximately 103 sq. in. of button screen for each tube or a total of 6180 sq. in. for all of the tubes. Because the tubes are closely spaced and equally distributed along the length of the tank and expose a relatively large sand area to the incoming oil, the sand in the reservoir can be charged in a relatively short time under a small differential pressure.

The maximum charging rate provided for in the installation is 40 gal. of oil per min., or ⅔ gal. per injection tube per min. It is anticipated, however, that the charging rate will decrease as the reservoir becomes charged with gas-saturated oil.

Although it is planned to take samples of the fluid at intervals of 10 ft. in the flow line, it is not known definitely at this time whether sufficient variations in temperature, pressure and density of the fluid can be detected in samples taken so close together. It is believed, however, that these variations are measurable, and preliminary runs will be made to decide the point definitely.

The maximum quantity of oil which should be removed from the sand before recharging the reservoir for the next run has not been determined. Preliminary experimental tests will be made to determine the percentage of depletion of oil from the sand at which all tests runs will terminate.

Conclusion

Only a brief résumé of the experimental equipment and contemplated methods of investigation of the problem of natural and gas-lift flow is possible at this time. Accurate data relative to quantities and volumes, time required to charge the reservoir, rate of reservoir depletion, and other information pertaining to the experimental work will not be available until the equipment has been thoroughly tested in every detail and runs have been made in accordance with the program of procedure.

It is hoped that the experimental tests will give a considerable amount of information on flowing conditions in vertical pipes and the effects of natural flow and gas-lift flow on the rate of recovery from reservoir sands which will have practical application in the field.

Acknowledgments

The Bureau of Mines appreciates the whole-hearted cooperation of many manufacturers of equipment and scientific instruments, jobbers of oil-field equipment, several of the oil companies and persons in the industry. Credit is due H. A. Buss, instrument maker at the Bartlesville Station of the Bureau of Mines, for his assistance in overcoming many mechanical difficulties.

Chapter III. Petroleum Production—United States

Production Development in United States during 1928*

By Joseph Jensen,† San Francisco, Calif.

(New York Meeting, February, 1929)

Total United States production for 1928 was 900,364,000 bbl. as compared with 901,129,000 for 1927, or 2,466,000 bbl. per day versus 2,468,000. The three major producing areas were Texas, Oklahoma and California. Texas production increased from 217,389,000 bbl. in 1927 to 256,888,000 in 1928—an increase of 39,499,000 bbl. following an increase of 44,500,000 bbl. in 1927. Oklahoma production amounted to 249,558,000 bbl. in 1928 as compared with 277,775,000 bbl. in 1927 and 177,650,000 bbl. in 1926. California production for 1928 was 231,982,000 bbl. as compared with 231,196,000 in 1927. Production increased markedly in Venezuela and declined in Mexico. Elsewhere no great changes or declines in production were noted. New discoveries occurred in nearly all districts.

The many excellent reviews of the various districts of the United States presented at this meeting, are each fully summarized and tell their own story so well that little would be gained by attempting to repeat their content here. There are certain impressions to be gathered from these papers and certain trends that are indicated by them which may better be pointed out.

Overproduction

Overproduction is the most serious one of them. Efforts to avert it resulted in a measure of cooperation in the oil industry more widespread in character and more beneficial in results than has ever been recorded in any previous year. These efforts were undertaken in the closing months of 1927 and enthusiastically effected before the spring of 1928 had passed. Unfortunately, slight advances in prices during the summer months accompanied by the letting down of this sort of effort resulted in a marked increase of production during the latter half of 1928.

Successful delay in the drilling of new prospective areas was in effect in Oklahoma. California delayed some drilling and increased its shut-in

* Published by permission of J. A. Taff, Chief Geologist, Associated Oil Co.

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production from a maximum of 93,000 bbl. per day in August of 1927, to a maximum of 133,000 bbl. per day in April and May of 1928. Production was curtailed in an outstanding way in the West Texas pools, particularly Hendricks and Yates. Wyoming has practiced controlled production in an exemplary manner for several years.

That there was a relaxing in effort is also shown in other ways. By Feb. 15, 1929, no major holding back in drilling will exist in Oklahoma. Increased pipe line outlets into West Texas will make possible the removal of much more oil. The development of the Santa Fe Springs field, and the opening up of heavy production in the Kern Front field in California, with the conditions described for Oklahoma and Texas, all serve to indicate that efforts toward the control of production lost some of their strength as the year passed.

Nevertheless, a great deal of good has come to the industry. All those engaged within it are being educated as to the causes of overproduction and the fact that it must eventually be controlled. Such education has already had its value. This is proved by the voluntary efforts of many operators in not extensively developing lands even though valuable discoveries have been made. Such efforts mean, however, that those operators pursuing such a policy are developing genuine reserves for their organizations. While both the small operator and the large operator have suffered from low prices it is interesting to note that the heavier burden of making the curtailment effort in 1928 has generally fallen upon the larger units of the industry.

These efforts at curtailment are worthy of consideration. Because of their variety, they serve to demonstrate those methods which may be expected to be successful and those which still have difficulties ahead.

Control of Production in California

California's most successful type of control was secured by the postponement of the development of deeper oil zones. In 1924 an agreement was made at Dominguez limiting the development to 400 ft. of oil zone. In 1925 an agreement was made in the Inglewood field limiting development to the first 1300 ft. of oil zone. The term of both of these agreements has ended but the good resulting from them may be expected to continue for the greater part of 1929, if not longer. California has also avoided a large quantity of oil by the complete shutting in of wells.

Practically all of the oil shut in in California was heavy oil. By this action the state avoided the production of approximately 42,000,000 bbl. During the preceding year the shut-in production was estimated at 25,000,000 bbl. of oil. Obviously the 42,000,000 bbl. of oil just mentioned also includes at least a third of the 25,000,000 bbl. held shut in the

preceding year. The effective amount of production that was avoided during 1927 and 1928 probably amounts to 50,000,000 to 55,000,000 bbl. of heavy oil.

Oklahoma's principal successful effort was the postponement of the development of new oil fields and the regulation of drilling around wildcats. Texas effected a curtailment based on acreage and production in such a way as to reduce drilling and limit the production of oil. Shutting in wells is usually only possible on lands owned in fee, but it has been successfully applied on leased lands for the past 2 or 3 years in the newly discovered and developed Round Mountain, Mount Poso and Fruitvale areas of California.

The very earnest attempt made in California to control flush production from the newly discovered deep sands at Santa Fe Springs met with failure although it was based upon sound and accepted engineering principles. In such a purely voluntary movement as attempted at Santa Fe Springs, there was lacking an adequate and satisfactory method of enforcing the program so as to assure those who refused to enter it that there would be full compliance. Besides a few operators "needed the oil." Past experience and this experience tends to demonstrate that any effort to control flush production in an intensively drilled town-lot area will fail until this missing element is added to the cooperative method. Texas regulation of production was successful in pools producing from limestone where the wells made no sand. California wells are subject to a wide range in production when opened up and are in danger of injury from sand at such times.

One of the outstanding efforts at curtailment has been that effected in the Ventura Avenue field by three operating companies even though two others refused to join with them. This movement was predicated upon a genuine desire to save gas and has been more successful because of the need of gas conservation than because of any attempt to control production.

Disposition of Surplus

While these three districts have each had a serious problem of overproduction to meet, it is interesting to note how each handled its surplus. In California gasoline was sold and the remaining fuel oil stored. In the Mid-Continent area, light oil was stored to the extent of approximately 19,000,000 bbl. East of California stocks of heavy crude showed little change during 1928. This indicates that Texas disposed of its heavy oil in such a way as to compete satisfactorily with the light oils of the Mid-Continent.

No matter how pessimistic or discouraged one may feel about the threatened overproduction for 1929, or fearful that 1929 may be like 1927, the many efforts at curtailment have demonstrated a most com-

mendable cooperative spirit within the industry. This work is now being undertaken with renewed effort. An understanding of the seriousness of the problem is bound to result in much good whether the final solution be in unit operation or in some other one of the many methods proposed. A few years ago any attempt at the regulation of wildcatting or the development of oil fields was frowned upon by the industry on the ground that it would destroy the initiative of the wildcatter. At the present time the industry is fully convinced a method of control must be created. The fear is not that the initiative of the wildcatter will be destroyed but that while it is unregulated the industry is being seriously injured.

Increased Use of Natural Gas

A second outstanding feature that has grown more apparent during the years 1927 and 1928, is the serious inroad which the use of natural gas is making upon the domain of fuel oil and coal. Pipe lines of large diameter and great length have been built and are being projected in many directions to communities in the Rocky Mountain states and in the Mississippi Valley. In California, the increase in the use of natural gas has been so great as to prevent any increase in the use of fuel oil during the past 3 years. The discovery of a new gas field in the San Joaquin Valley and the finding of the Kettleman Hills oil field indicate that the use of natural gas in Central California will be rapidly extended. Consumption of natural gas in Southern California displaces more than 40,000 bbl. of fuel oil per day. Not only is natural gas a competitor in industry with fuel oil and coal but it is also a competitor in the oil fields. About the only instance in which natural gas has been displaced is in cement plants using cracking still residuum. The many new gas lines projected or under construction for the year 1929 indicate that this sort of competition will continue for another 3 to 5 years throughout the country. If the discovery of new fields with the attendant gas continues, this same sort of competition will increase.

Gas Economy

The extensive use of the gas-lift, the engineering discussions on gas-oil ratios and the widespread understanding of the importance of gas in producing oil are being rapidly advanced in California. This is due to the cooperative efforts of oil companies which they themselves first initiated in the Ventura Avenue field and later fostered in 1928 at the instance of the Governor of California. As the result of these efforts, large volumes of gas have been stored in old fields. Wasteful wells having high gas-oil ratios have been shut in, others have been pinched back,

and withdrawing gas from the casingheads for field usage where the wells were shut in has been discontinued. Approximately 140,000,000 cu. ft. per day are thus being conserved. This has been an approximate value of $10,000 to $14,000, and represents over 20,000 bbl. of fuel oil based on heating equivalents. These discussions have served to bring out very clearly the important part played by gas in increasing the recovery of oil and in permitting its production at the lowest possible cost. They have served to bring out the fact that there is no possible substitute for, or other method of recovery of oil that can be as efficient as the judicious use of the gas found, associated with, and in solution in the oil.

The great economic value of the gas so produced has been emphasized. During the period of tremendous overproduction in 1923 little or no thought was given to surplus gas blown in the air. Saving gas in different ways is now under way in California. Similar action will follow in other districts throughout the United States, since both the oil company and the gas company will be interested in this work.

New Developments in 1928

The reviews of the various districts also bring out in a striking way the fact that each new discovery in the past few years has taught a lesson that led to many other new discoveries. This is illustrated by the discovery at Seminole in 1926, the entrance into West Texas in 1921, and the discovery of oil by deeper drilling at Signal Hill.

Thus, in 1928, the most important development in Louisiana saw the finding of oil at Sorrento, east of the Mississippi River. The actual finding of this oil upsets older theories and opens up possibilities which may extend into Mississippi and possibly as far east as Florida. Numerous instances will be found in following these reviews where new discoveries within established districts and areas that were looked upon with little favor have been made in 1928. Such discoveries promise more intensive searching in the future. The tendency toward deeper drilling in Reagan County, Texas, and in California in 1928, may eventually furnish quite as much new oil from beneath existing fields as the opening up of virgin territory elsewhere. The use of the torsion balance, the seismograph and magnetometer illustrates new methods for finding structures. The persistent drilling of salt domes in the Gulf Coast area, usually resulting in many disappointments, but also occasional discoveries, promises much oil for the future because of the many new structures these methods have found.

Production, Consumption and Stocks, 1920–28

Changes in production, consumption and stocks during the past 8 years are shown in Table 1. Only in 1926 was there a decrease in stocks. This amounted to 24,764,000 barrels.

TABLE 1.—*Changes in Eight Years*

	Production, Bbl.	Production Plus Imports, Bbl.	Consumption Including Exports, Bbl.	Stocks, Bbl.
1920	442,929,000	551,723,000	522,309,000	221,460,000
1928	900,364,000	1,035,456,000	1,008,959,000	609,112,000
Increase	500,897,000	483,733,000	486,650,000	387,652,000
Percentage increase	113	88	93	175

It should be evident to all concerned that during the past 8 years scientific developments within the industry, in finding new fields, in producing oil and in utilizing oil at refineries have more than kept pace with growing consumption. The end of such commendable efforts is not yet in sight. They may be expected to continue in the same manner for many years to come. They therefore indicate that the greatest problem which the industry has to solve is the one of overproduction. The successful efforts in this regard in 1928, and those planned for 1929, are encouraging indications that much can be done and that much will be done in the way of intelligent regulation, curtailment and conservation.

DISCUSSION

H. D. HANCOCK,* New York, N. Y.—One of the largest single natural-gas developments during the past year, and in fact for a number of years, has been the construction of a 20-in. high-pressure pipe line from the Amarillo gas field in the Texas Panhandle to Kansas City, Mo. This line is approximately 420 miles long and has 27,000 hp. in compressor-station capacity in six compressing stations along the line.

During the past year, an important new natural-gas line has been completed from the Texas Panhandle field to Pueblo and Denver, Colo. This line is 341 miles long, is 22 in. in size from the field to Pueblo and 20 in. from Pueblo to Denver.

It has recently been announced in the gas journals that 450 miles of pipe line, probably 22 in. dia. will shortly be constructed from the Monroe, La., field to St. Louis, Mo.

During the past year 212 miles of 18-in. line was completed from the Monroe field to Memphis, Tenn. During 1928 natural gas was introduced into New Orleans, La., by means of an extension of the existing Monroe-Baton Rouge line to New Orleans. A number of other important developments are in progress, such as the construction of a line from Lee County to El Paso, Tex., and the construction of another line 270 miles long from the Baxter Basin field to Salt Lake City. Natural gas was also discovered in Michigan and has been piped to Muskegon and nearby industries and towns. A large gas development has also taken place in Montana, although there are not as yet any major pipe lines in course of construction.

In the development of a natural-gas project there are three important considerations—production, transportation and marketing. It is necessary for the gas industry to ascertain carefully that these three phases of any project have been properly analyzed and that the decision about each is based on carefully developed facts. Perhaps the production and marketing phases of a natural gas project are the most important

* Henry L. Doherty & Co.

or, at least, susceptible to widest variation of judgment. The transportation problem can be solved with fair accuracy. If, however, the estimate of gas supply and field price during the entire period is inaccurate the project will be unsound and, on the other hand, if the available market is wrongly estimated, both as to quantity and price, the project is not a good one. It might be well to mention at this point that in considering major natural gas projects it must be borne in mind that the established coal and fuel oil business in each community will not be disturbed without resistance on the part of the coal and oil dealers.

Oil Production and Development in Oklahoma in 1928

By E. P. Hindes,* Bartlesville, Okla.

(New York Meeting, February, 1929)

The total amount of oil produced in the state of Oklahoma during the year 1928 was 242,286,400 bbl., as compared to 273,372,650 bbl. in 1927; 177,650,000 bbl. in 1926; and 167,900,000 bbl. in 1925. The year 1928 ranks second to 1927 in which more oil was produced in the state than in any previous year. The large production in 1927 and 1928 was due principally to the development of the Greater Seminole district. The decrease of approximately 31,000,000 bbl. in the 1928 production as compared with the production in 1927, was caused by a drop of nearly 8,500,000 bbl. in the Seminole district production and a more or less normal decline in the production of practically all the other older and more settled fields.

During 1928 approximately 1800 producing wells were drilled in Oklahoma, which yielded during the year approximately 90,000,000 bbl. of oil. The average initial production of these wells was 850 bbl. per day, and the average daily production per well for the year was 137 bbl. The average daily production per well of the total number of wells producing in 1928 was 10.9 bbl., which is a 13.5 per cent. decrease from the 1927 average of 12.6 barrels.

At the close of 1928 a total of 95,400 producing wells had been drilled in the state, and approximately 61,000 were still producing. The grand total amount of oil produced in the state from the time the first well was drilled up to and including 1928 was 2,553,000,000 bbl. The production in 1928 was 9.5 per cent. of the total oil produced in the state.

Texas led all other states in 1928, with a production of 251,835,200 bbl. Oklahoma was second with 242,286,400 bbl., and California was third with 231,982,600 barrels.

Fields outside Greater Seminole District

Practically all the old settled fields in Oklahoma experienced a normal and expected decline during the year 1928. The fields showing the most pronounced decline as compared to 1927 were: Burbank, which dropped from 15,230,400 to 11,939, 150 bbl.; Tonkawa, from 7,692,000 to 4,952,900 bbl.; Garber, from 5,056,300 to 3,139,400 bbl., and Wewoka, from 6,188,-800 to 2,450,400 bbl. There were no new extensions, discoveries of

*Empire Oil & Refining Co.

deeper sands, or other developments of especial consequence during the year in the old fields.

The only new development in Oklahoma of particular significance during 1928 other than in the Greater Seminole district was the well drilled by the Indian Territory Illuminating Oil Co. near Oklahoma City. All other new discoveries failed to develop sufficient production, or potential possibilities, to cause them to have an important bearing on the total production of the state. The production developed in 1928 from discoveries, and from additional drilling in old fields, did not equal the normal decline of the old fields, as the state outside of the Seminole district showed a decrease of 22,521,550 bbl. in 1928 as compared to 1927.

No. 1 Fee well of the Indian Territory Illuminating Oil Co., near Oklahoma City, is in the center of SE. 1/4 SE. 1/4 sec. 24, 11N., 3W., Oklahoma County, which is approximately 45 miles northwest of the nearest production in the Seminole district. The well was completed Dec. 4, 1928, at a depth of 6404 ft., and had an initial production of 4909 bbl. It was gradually deepened to 6499 ft. and on Jan. 2, 1929, the production increased to 6464 bbl. The gravity of the oil is 38.5° Bé.

There is considerable difference of opinion among those who have studied the well as to the formation from which it is producing. Since the deepening of the well the prevailing idea seems to be that the oil is coming from the basal Simpson or from the Arbuckle limestone, or possibly from both of these formations. This correlation is not definite and may have to be changed when more information is obtained. It will require much more drilling to determine the possibilities of the area, and development will be considerably retarded by depth and high cost of drilling. The size of the discovery well and the quality of the oil are encouraging and indicate that drilling is justified even at the extreme depth at which the production is found. There is no way to estimate the size of the productive area, or the amount of production that will be developed, but considering that the discovery well is located on a large surface structure, there is good reason to believe a major field has been discovered. Considered on this basis, and that it opens up a large area for prospecting in which other pools will probably be discovered, the potential significance of the well is very great.

Greater Seminole District

The Greater Seminole district was the outstanding development in Oklahoma and in the Mid-Continent field during 1927 and 1928, and promises to be a very important factor for some time in the future. The oil produced in this district has had a pronounced influence on the price structure and on the general trend of the petroleum industry. Consider-

ing that the Greater Seminole district produced 52.7 per cent. of the total production of the state, this area is the most important actual and potential factor in a consideration of oil production and development in Oklahoma in 1928.

The Seminole district was discovered by the Indian Territory Illuminating Oil Co., in March, 1926, when that company completed a 1100-bbl. Hunton lime well in sec. 24, 9N., 6E., Seminole County, at a depth of 3900 ft. The first Wilcox sand production was developed by the Independent Oil & Gas Co. and R. S. Garland in July, 1926, when they completed an 8000-bbl. well in this horizon at a depth of 4069 ft. The completion of the Independent and Garland well started an intensive drilling and wildcatting campaign in this general area, and many pools, or potential pools, were discovered in rapid succession.

The district was developed so rapidly, and proved so prolific, that a peak production of 529,596 bbl. per day, from 666 wells, was reached July 30, 1927. The total production of the district in 1927 was 136,104,000 bbl., and amounted to 127,656,000 bbl. in 1928.

At the beginning of 1928 six pools had been opened, and five of them developed beyond their peak production. In addition, seven potential pools had been discovered, but were not being developed on account of curtailment agreements. The six developed pools were Seminole City, Searight, Earlsboro, Bowlegs, Pearson, and Little River. A list of the seven potential pools discovered in 1927, and a discussion of the development in the area in 1928 are given in Table 1.

Three new pools were discovered during 1928 in the Greater Seminole area. The first was the St. Louis pool, which was opened by a well drilled by the Mid-Continent Petroleum Co. in sec. 25, 7N., 4E. and completed Feb. 10, with an initial production of 2007 bbl. The active drilling campaign in this area was started by the completion of a well by the Magnolia Petroleum Co. in sec. 19, 7N., 5E. on June 14. It had an initial production of 8970 bbl. from the Wilcox sand. The pool developed rapidly and produced a total of 21,252,900 bbl. during the year.

The second well which appears to open a new Wilcox sand area was that of the Sinclair Oil & Gas Co. in sec. 7, 5N., 8E., which was completed Sept. 21, and estimated to have an initial production of 1000 bbl. This well is in the Allen pool, which is almost completely developed in the shallower sands. The well was shut in and no other Wilcox-sand wells were completed in this area in 1928.

The third well to open a new pool was that of the Gypsy Oil Co. in sec. 7, 8N., 5E., which was completed Aug. 31, 1928, with an initial production of 1790 bbl. from the Hunton lime. Approximately 20 more producing wells were completed and 80 more operations were started in this area in 1928. A pool of considerable size seems assured.

TABLE 1.—*Potential Pools Discovered in 1927 in Seminole District*

Company and Well	Location	Date of Completion	Initial Production, Bbl.	Producing Sand	Depth, Ft.	Remarks
1. Gypsy Oil Co. No. 1 Clinty Brown.	Sec. 33, 8 N., 6E.	March 29	592	Wilcox	4,539	Development in this area in 1928 was discouraging. Three producing wells and three dry holes were drilled. A pool may be developed, but prospects are unfavorable.
2. Prairie Oil & Gas Co. No. 1 Baker.	Sec. 24, 9 N., 5E.	May 23	1100	Wilcox	4,315	No wells were completed near the discovery well during the year. Development in the Earlsboro pool indicates that the well may be included in a southeast extension to that field.
3. Gypsy Oil Co. No. 1 Mission.	Sec. 5, 8 N., 6E.	July 12, temporarily completed; shut in and completed June 11, 1928	3210	Wilcox	4,327	Discovery well in Mission pool. Ten more wells completed in this area in 1928 and presence of a pool was well established. All wells completed or now drilling, upon which discovery rights have been waived, may be opened for production Feb. 15, 1929. This action caused starting of approximately 85 wells late in 1928. Several drilling wells running low, and results of drilling in this area are somewhat uncertain.
4. Independent Oil & Gas Co. and Highway Oil & Refining Co. No. 1 Holuka.	Sec. 23, 7 N., 6E.	Nov. 6	2350	Wilcox	4,325	Discovery well in South Little River pool, which was practically completely developed during 1928, and proved to be an extension to Little River pool. Production from this pool and the south extension was 24,790,650 bbl. of oil in 1928.
5. Snowden & McSweeney No. 1 Tiger.	Sec. 13, 7 N., 6E.	Nov. 24	744	Wilcox	4315	As area was developed this well was found to be included in the productive area of the South Little River pool.
6. Mid-Continent Petroleum Corpn. No. 1 Smith.	Sec. 5, 7 N., 7E.	Dec. 9	1250	Wilcox	4440	Only three more producing wells were completed in this area in 1928. The area appears favorable for the development of a pool of considerable size, but only additional drilling will determine the possibilities of the area.

TABLE 1.—(*Continued*)

Company and Well	Location	Date of Completion	Initial Production, Bbl.	Producing Sand	Depth, Ft.	Remarks
7. Barnsdall Oil Co. and Wolf Oil Corpn. No. 1 Fife.	Sec. 14, 8 N., 5E.	Dec. 11	1,396	Wilcox	4,292	Four more producing wells were completed and 20 operations begun near the discovery well in 1928. These indicate presence of a pool the size of which can be determined only by additional drilling.

PROSPECTING ACTIVITIES

There was less wildcat drilling in Oklahoma during 1928 than in former years. This condition was due to the general depression in the petroleum industry, caused by overproduction and accompanying low price of oil. There was also less field geological work, except that done by geophysical instruments, which materially increased, and by core-drilling.

Most of the larger oil companies curtailed their own wildcat drilling and were reluctant to support the operations of promoters. The result of this decreased drilling was the failure to discover, during the year, any new production of consequence outside of the Greater Seminole district and Oklahoma City.

Most of the prospecting activities were in the central and western parts of the state. The counties receiving the most attention were Logan, Oklahoma, Pottawatomie, Cleveland, McClain, Garvin, Canadian Blaine, Major and Woods. Geophysical instruments were used quite extensively in this area as well as in the extreme southwest part of the state. The activity was confined principally to leasing checkerboard acreage, or blocks of sufficient size to make drilling units, and very little drilling was done. The Greater Seminole district received considerable attention, and a number of wildcats were drilled, the majority of which were necessary to protect short time leases.

CONSERVATION

In the fall of 1926, after the discovery of the Wilcox sand in the Seminole City pool in July, the owners of acreage and production in the Seminole district met in Tulsa to discuss ways and means to control the flood of oil that was being developed. They appointed a committee and umpire to make a survey of conditions and report their findings, with recommendations, at a meeting to be called by the committee. From these meetings developed the present organization, and plans for the control of production in Oklahoma. The conservation organization is as follows:

1. An advisory committee, consisting of four representatives of the larger companies and three representatives of the producers not having affiliations with any pipe lines or refineries.

2. A legal committee of five attorneys, elected by the producers, who confer with the umpire, the advisory committee and the Corporation Commission.

3. An umpire appointed by the producers and the Corporation Commission.

4. The Corporation Commission of the State of Oklahoma, and the Attorney General of the State.

This organization, with the cooperation of the owners of producing or potential wells, endeavored to relieve a serious overproduction situation which developed and became acute in July, 1927, when the Seminole district reached a peak production of 529,526 bbl. per day. The Corporation Commission issued an order limiting this production to 450,000 bbl. per day, and in varying degrees production in the Greater Seminole area has been held back by proration and curtailment ever since.

The greatest results of the conservation movement in Oklahoma were attained, not through proration but by shutting in producing wells, or wells which appeared to have possibilities of opening new pools at a time when additional large flush production would have caused disaster to the industry.

It would be difficult, and perhaps impossible, to show the actual results of this conservation movement during the year 1928, for to understand the situation in any degree would require a detailed study of each individual area. In some cases the area has not been drilled and only a guess can be made as to the quantity of oil that might have been developed had drilling proceeded on all locations where it appeared good production might be secured.

The efforts toward conservation in Oklahoma in 1928 accomplished beneficial results, but the application of conservation measures met with many obstacles. The subject received very serious consideration by many individuals and organizations who wished to contribute to the best interests of the industry, but no entirely satisfactory or dependable method of regulating the production of oil to the proper relation to demand was put in effect.

Petroleum Development in Southwest Texas during 1928

By Olin G. Bell,* Laredo, Tex.

(New York Meeting, February, 1929)

During the year 1928 ten new producing areas have been discovered and several extensions in oil and gas fields have been found in southwestern Texas. This year, however, will reveal itself as one of small profits in spite of considerable increase in production for the area as a whole over the previous years.

At the beginning of 1928 the fields in this area (Fig. 1) were producing a daily average of 7500 bbl. from 730 wells, whereas at the close of the year the daily average had increased to approximately 14,000 bbl. from 827 wells. Production for the year was 3,453,938 bbl. The total oil produced in Southwest Texas since its discovery has been 16,955,488 barrels. (Table 1.)

Table 1.—*Summary of Southwest Texas Fields*

Field	Total Production Since Discovery of Field, Bbl.	Daily Production, Dec. 31, 1928, Bbl.	Producing Wells, Dec. 31, 1929	Daily Average Production per Well, Dec. 31, 1928, Bbl.
Randado (including Alworth)	2,417,593	1,614	154	10.6
Aviators	3,184,937	1,319	.161	8.2
Henne-Winch-Fariss	2,801,188	312	80	3.9
Schott-Mirando City	3,996,330	766	111	6.9
Mid-Ojuelos	1,861,903	359	71	5.0
Wolcott	452,138	101	20	5.0
Mirando Valley	368,739	59	12	4.9
Cole-Bruni	559,840	2,310	35	66.0
Albercas	712,691	4,981	35	142.3
Charco Redondo	42,382	123	111	1.1
Carolina-Texas	32,649	34	3	11.3
Kohler	30,483	50	4	12.5
Government Wells	35,637	564	7	80.6
Palangana	1,873	13	1	13
Cuellar	30,103	332	7	47.4
Refugio	71,592	669	3	223.0
Kingsville	355,410	293	12	24.4
Total	16,955,488	13,899	827	

* Division Geologist, Humble Oil & Refining Co.

New Pools

Albercas Pool

The Albercas field is in reality a northeastward extension from the Henne-Winch-Fariss field and about 5 miles southeast of the old Aviator field along the Reynosa escarpment in Webb County. The discovery well was the O. W. Killam No. 8 Bruni, completed May 18, 1928, as a 900-bbl. well. Shows of both oil and gas had been encountered in wells in this locality in 1927 but no commercial production developed. Since then 79 wells have been drilled, 19 of these have been dry and abandoned, 12 have been gas wells and 48 are producing oil wells. Development is being continued in this field during 1929.

The depth of the sand is approximately 2180 ft., the same as in the Henne-Winch-Fariss field, and is no doubt the same sand. The gas wells range from 25,000,000 to 40,000,000 cu. ft. of gas. The average daily production in this field during December was 4981 bbl. Pipe-line runs totaled 722,146 bbl. and number of producing wells varied from 4 to 39.

Government Wells Pool

The Government Wells pool is in the old Government Wells Ranch in northwestern Duval County, about 35 miles northwest of San Diego. Drilling was begun in this area in the latter part of 1926, when H. B. Schlesinger et al. began their No. 1 Hahl, Survey 76. This well and five subsequent ones in the same general area were failures. The S. & O. Oil Co., however, completed its No. 1 Norton in Block 19, Survey 250, a short distance west of these dry holes, in August, 1928, as a 2500-bbl. well in a sand from 2338 to 2350 feet.

During 1928 11 wells were drilled in this area, of which nine were oil producers, one completed as a gas well and one dry. The average daily production from seven of these wells during December was 564 bbl., or an average of 80.6 bbl. per well per day. The total of pipe-line runs for the year 1928 was 35,637 bbl. The number of wells varied from one to seven.

This productive horizon consists of two or more sands separated by thin shale partings near the middle of the Fayette (Upper Eocene) formation. This field marks the continuation of a productive trend from the Carolina-Texas field in Webb County northeastward in close proximity to the Reynosa escarpment, a marked topographic feature in southwestern Texas.

Agua Dulce Area

The Agua Dulce field, about four miles southeast of the town of Agua Dulce in western Nueces County, was discovered by the first well

drilled in this area; namely, the H. F. Grimm et al. No. 1 Garrett in section 34, completed in August as a gas well with 35,000,000 cu. ft. of gas and a reservoir pressure of 860 lb. The productive sand is from 2016 to 2023 ft. and is in the late Tertiary, probably Pliocene, although its

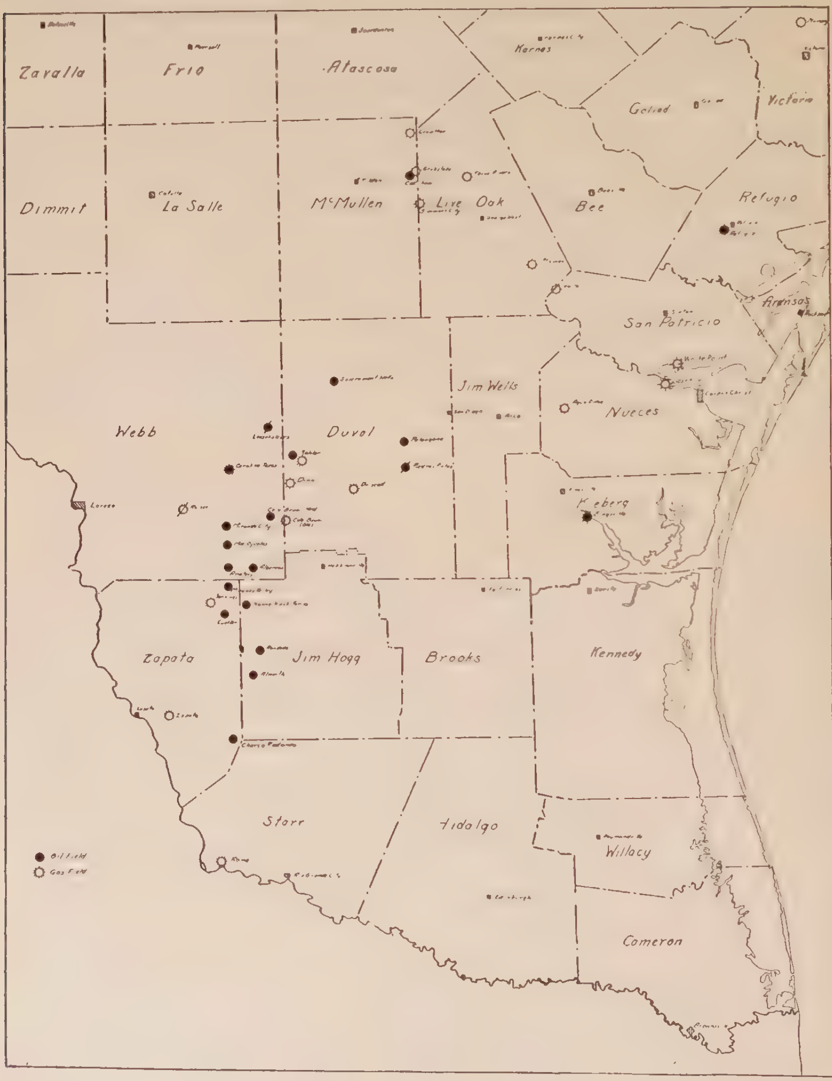

FIG. 1.—PRODUCING AREAS OF SOUTHWEST TEXAS.

exact stratigraphic position has not as yet been determined. The type of structure is not yet known. Three additional gas wells have been completed in the immediate vicinity of the discovery well and three dry holes have been drilled about 2 miles away both north and southeast.

The towns of Alice and Agua Dulce are being supplied with gas from this field by the Houston Gulf Gas Co.

Cuellar Pool

This pool is about 6 miles south of the old Mirando Valley pool in Zapata County, the discovery oil field in the Laredo area, and is 4 miles west from the Henne-Winch-Fariss field. It was discovered by the O. W. Killam No. 1 Cuellar which was completed Sept. 6, 1928, as a 250-bbl. oil well. The producing sand here ranges from 1440 to 1460 ft. Nine wells were drilled during 1928, all of which were producers; two were gas wells and seven were oil wells. There is a daily average of 332 bbl. in this pool. Pipe-line runs from Cuellar field totaled 30,103 bbl. for the year, the number of wells varying from two to seven.

Driscoll Pool

The Driscoll gas pool was discovered by Robert Driscoll while drilling water wells on his ranch in south central Duval County. The discovery well was completed in 1927 as a gas well having 30,000,000 cu. ft. of gas with 700 lb. reservoir pressure in a sand from 2444 to 2468 ft. This productive horizon is probably Oligocene. The type of structure has as yet not been determined. Another producing sand has been found at 2936 ft. Inasmuch as this area lies several miles from the outer boundary of Mr. Driscoll's ranch, and none of his land has been leased to outside interests, there has been only an unexcited and orderly attempt by Mr. Driscoll to develop the pool. The only well drilled off the Driscoll ranch was Edward St. Albans' No. 1 Hyatt, about 2 miles northward. This well was abandoned as a failure at 3075 ft. Since the discovery of gas, five additional gas wells have been completed in the 2400-ft. sand and two others completed in the 2900-ft. sand. The wells range from 15,000,000 to 40,000,000 cu. ft. of gas, with reservoir pressures ranging from 500 to 1000 pounds.

Kohler Gas Pool

Late in 1928 the Humble Oil & Refining Co. encountered gas in the central part of the Kohler ranch in west central Duval County, in a sand at 1850 ft. which had proved nonproductive in other wells drilled on the ranch. The discovery well was No. 9 Kohler, and two new gas wells have been completed in close proximity. The productive horizon is Upper Fayette (Upper Eocene). These wells are 2 miles southeast of the oil wells producing from a 2800-ft. sand.

Clay Creek Dome

Late in 1928 the Sun Oil Co. found production in Washington County about 12 miles north of Brenham and near the town of Independence,

on what is termed the Clay Creek dome. Aside from core-drill tests, the first well drilled was No. 1 Schirmer, abandoned dry at 4178 ft. Next, No. 1 Grote was completed as a small producer in a sand from 1140 to 1154 ft. No. 2 Grote, drilled 600 ft. northwest of No. 1, failed to produce from the 1150-ft. sand and was deepened to 1390 ft., where production was found. On account of lack of storage, a good gage has not been made on this well, but when opened it flows at the rate of 200 bbl. per hour. No. 1 Grote was subsequently deepened to the 1400-ft. sand and completed as a 200-bbl. well.

The Cook Mountain (Middle Claiborne-Eocene) is encountered here at 600 ft. and the producing horizon is a member of that formation. This is the first occurrence of Claiborne production of any importance in Southwest Texas. Both the 1150 and 1390-ft. horizons are in a sand member that is about 175 ft. thick.

No production was marketed during 1928 but a pipe line has been laid from the field to Gay Hill, a station on the Santa Fe Railway, 6 miles away and the production will be shipped from there by tank cars to the coast. This oil has a gravity of 26° Bé.

Nursery

During the year the Humble Oil & Refining Co. continued development of a shallow gas sand near Nursery in Victoria County. Several small wells have been completed at approximately 700 ft. These wells have been drilled for structural purposes rather than for gas production.

Roma Shallow Gas Field

The Texas Co. in drilling the Roma structure, slightly west of the town of Roma on the Rio Grande in Starr County, encountered gas at 198 ft. and completed two wells in this shallow sand. The gas from these wells has been used for fuel in drilling other deep tests on the structure. These small wells were completed in April, 1928. The surface formation here is Yegua (Upper Claiborne-Eocene).

Porcion 30, *Zapata County*

Late in 1927 a water well being drilled near the east end of Porcion 30 in Zapata County, about 10 miles east of the town of Zapata, encountered a small show of gas at 165 ft. Early in 1928 the Wolcott Petroleum Co., of Laredo, drilled another well near by in Porcion 29 and found a small amount of gas at 179 ft. The volume was estimated at 100,000 cu. ft. The productive horizon is probably Lower Fayette (Upper Eocene). This production is too shallow and too small to be of more than local importance.

Old Fields

Schott-Mirando City Field

The Schott-Mirando City field,[1] one of the older Reynosa escarpment pools, has led all other pools in southwest Texas in production to date. Up to the close of 1928 it has produced 3,996,330 bbl. of oil. The field, however, has long passed its peak and during December had a daily average of only 766 bbl. from 111 wells, or a daily average of only 6.9 bbl. per well. Production is from a 1700-ft. sand in the Fayette. Pipe line runs from the field totaled 629,681 bbl. during 1927 and 492,503 bbl. during 1928. There were from 210 to 218 wells producing in 1927, while the number varied from 202 to 216 in 1928.

Five wells were drilled during the year, four were abandoned as failures and one completed as an oil well. O. W. Killam's No. 1 Killam drilled in the townsite of Mirando City was an effort to find a northward extension from the main part of the field. This was a failure.

Aviator Field

The Aviator Field, on the Reynosa escarpment in southeastern Webb County, is one of the earlier discoveries of this area. It reached its peak late in 1927, and now stands second in point of total production. Up to the close of 1928 it has produced 3,184,937 bbl. from a 1700-ft. Fayette sand. During December the daily average was 1319 bbl. per day from 161 wells. The pipe-line runs totaled 854,626 bbl. in 1927 and 531,363 bbl. in 1928, from 175 to 180 wells in 1927 and from 143 to 167 in 1928.

This is the only field along the Reynosa escarpment which has been wider than from 400 to 800 ft. In one place the width of the outlined productive area exceeds 1½ miles.

During the year three wells were drilled in this field, two of which were abandoned and one completed as a gas well. The two wells abandoned were east of the producing zones and were drilled in an effort to pick up either the new producing sands or to find the producing sands a little higher than in the main part of the field.

Mirando Valley Field

The Mirando Valley field, northeast Zapata County, is the original discovery field of this area opened in 1921. During the year of 1928 four wells were drilled, three of which were abandoned as failures and one completed as a gas well. The main producing sand here is about 1500 ft. The Gleason Oil Co. completed its No. 1 as a 25,000,000 cu. ft. gas well with 440 lb. reservoir pressure in a sand from 1491 to 1497

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[1] The so-called Wolcott and Mid-Ojuelos pools have been included in the Schott-Mirando City field.

ft. Its No. 2 was dry and was abandoned at 1747 ft. W. R. Jewell's Nos. 1 and 2 Hinnant also were failures. The field, up to the close of 1928, has produced 368,739 bbl. of oil and has been, therefore, a field of lesser importance. During December the daily average for the field was 59 bbl. from 12 wells, or an average of 4.9 bbl. per day per well. Pipe-line runs from the field totaled 32,186 bbl. in 1927 and 27,753 bbl. in 1928, the number of wells varying from 19 to 20 in 1927 and from 14 to 19 in 1928.

Henne-Winch-Fariss Field

The Henne-Winch-Fariss field, in northwestern Jim Hogg County, was opened in 1925. The oil productive area has been fairly well defined but the gas acreage has not as yet been delimited. This has been one of the principal fields of the Reynosa escarpment area. Production comes from a Fayette sand ranging from 2000 to 2100 ft. deep. During the year four new wells were drilled, three were abandoned, and one was a gas well. These wells, however, were all drilled in the north end of the field in an effort to connect the production between the Henne-Winch-Fariss field and that in the newly discovered Albercas pool, 2 miles northward. In the central and southern part of the field several of the earlier producing wells have been abandoned. Pipe-line runs totaled 506,438 bbl. from 112 to 130 wells in 1927 and 188,515 bbl. from 82 to 113 wells in 1928.

Randado Field

The Randado field, in the western part of Jim Hogg County, and producing from a Fayette sand at 1260 ft., has been one of the most productive fields in this area. To Jan. 1, 1929, this field has produced 2,417,593 bbl. of oil and has been exceeded only by the Schott-Mirando City, Aviators, and Henne-Winch-Fariss fields, each of which are considerably older than the Randado. The field is now on the decline and the productive area has been quite well defined. The average daily production for December was 1614 bbl. per day from 154 wells. Pipe line runs from the field (including Alworth) were 1,070,874 bbl. in 1927 and 630,357 bbl. in 1928. Number of operating wells varied from 126 to 148 in 1927 and from 129 to 159 in 1928.

During the year 25 wells were drilled, of which 10 were failures and 15 were oil producers. Several of these deserve special mention: T. J. Conway's No. 1 Palacios in Survey 232, about 2 miles southeast of the field, was abandoned dry at 2317 ft. W. C. Berg's No. 1 Hinnant in Survey 19, about 2 miles northeast of the field, was abandoned dry at 2033 ft. H. L. Lightfoot's No. 1 Palacios in Survey 287, about 1 mile east of the field, found the Randado horizon structurally low and ended in a

failure. These wells were each drilled in an effort to pick up a new trend of production.

Several wells were also drilled in the field to greater depths in an effort to find lower producing horizons. Magnolia Petroleum Corporation's No. 41 Merchant State Bank, in Survey 155, was, at the close of the year, drilling at 2978 ft. No new producing horizon has been found. Early in 1928, however, the American Well & Prospecting Co. found a new sand 2 or 3 ft. lower than the main producing horizon and drilled several wells to it, which augmented the production considerably on their leases. This sand, however, has not proved to be very extensive and this production has not been long-lived.

Alworth Field

The Alworth pool, usually regarded as a southern extension from the Randado field in Jim Hogg County, was fairly inactive during the year. Four wells were drilled; one was abandoned, one was completed as a gas well and two as oil wells. The production in this field comes from a sand in the Fayette at approximately 1000 ft. The one gas well was small, having an initial volume of about 10,000,000 cu. ft. The oil wells are small and have an average initial production ranging from 5 to 10 bbl. Pipe-line runs are included in those of the Randado field.

Carolina-Texas Field

The Carolina-Texas field, on the Reynosa escarpment about 8 miles north of Mirando City in eastern Webb County, was opened late in 1921 as a gas-producing field in a 2000-ft. Fayette sand. Later gas production was developed in sands at 2100 ft., 2600 ft. and 3000 ft. During 1926 this field created some excitement through the finding of 36° Bé. oil in the 2600-ft. sand. The discovery oil well, however, which came in making 2700 bbl. per day, did not hold up long and offset wells failed to find production. Later the one oil well was completed in the 3000-ft. sand.

Up to the close of 1928 the field has produced 32,649 bbl. of oil and during December the daily average production was 34 bbl. from three wells. Pipe-line runs totaled 9156 bbl. during 1927 and 7142 bbl. during 1928. Number of producing wells varied from two to three in 1927 and from two to four in 1928.

During the year four wells were drilled, two of which were dry and abandoned, one completed as a 50-bbl. well in the 2600-ft. sand and one as a small gas well.

Cole-Bruni Field (Old)

The old Cole-Bruni field, in southwestern Duval County, about 12 miles east of the Reynosa escarpment, is primarily a gas field opened

late in 1925, although a few wells produced oil for a short time in 1926. The production is from a 1780-ft. sand near the base of the Frio formation.

The field has been fairly well delimited. During the year 18 wells were drilled, of which 7 were abandoned and 11 completed as gas wells.

Cole-Bruni (New)

The new Cole-Bruni field, 8 miles east of the Reynosa escarpment in eastern Webb County, derives its name from the old Cole-Bruni gas field four miles eastward in Duval County. This field was opened in 1927 and development has been prosecuted vigorously during 1928. During the year 64 wells were drilled, two of which were abandoned, seven completed as gas wells and 55 as oil wells.

During December this field had a daily average of 2310 bbl. from 35 wells, or a daily average of 66 bbl. per well. Since its discovery this field has produced 559,840 bbl. Production comes from a 2300-ft. sand in the Fayette. Pipe-line runs totaled 495,537 bbl., the number of producing wells varying from 1 to 35.

During December, J. J. O'Hern's No. 1 Benavides in Survey 697, about 2 miles northward, was completed as a 40,000,000 cu. ft. gas well in the 2300-ft. sand. This probably marks an extension of the productive area.

The Houston Gulf Gas Co. also completed a new gas well in Survey 693 about one mile northeast of the field proper, in a sand at 2299 ft. This appears to be another sand and doubtless marks a productive area in that sand.

Kohler Oil Field

The Kohler field, at the foot of the Reynosa formation in western Duval County, was opened by the Humble Oil & Refining Co. in 1927. Two producing wells were completed during 1927 and two additional ones completed in 1928. Production comes from a Fayette sand at 2800 ft. The wells are small, averaging about 25 bbl. of oil per well per day. Pipe-line runs totaled 5786 bbl. for the last two months of 1927, and 24,637 bbl. for the year 1928. There were two producing wells in 1927 and from two to four in 1928.

Leaseholders Field

This is an abandoned oil field in northeastern Webb County, about 6 miles from the Reynosa escarpment. An attempt to reopen this field was made by J. H. Winch et al., who drilled their No. 1 Gates to 530 ft. and abandoned it as a dry hole last March.

Reiser Pool

Four wells were drilled in the old Reiser field, an abandoned gas field in Webb County, during the year 1928. Two of these were shallow, one being drilled to 2806 ft. and another to 3501 ft. All four were failures.

Jennings Pool

During the year two new wells were drilled in the old Jennings gas field, Zapata County. These were Nos. 1 and 2 Jennings, of the South Texas Production Co., each completed as a gas well in the 1400-ft. sand and having a rock pressure of 500 pounds.

Charco Redondo Field

This is a shallow field, in southeastern Zapata County, having some oil production in a sand at about 170 ft. During the year, however, two deep wells were drilled and completed as gas wells. These were drilled by W. R. Duke. The gas horizon is about 975 ft. and the wells have an initial production of about 15,000,000 cu. ft. with 250 lb. reservoir pressure.

This field averaged 123 bbl. of oil per day from 111 shallow wells during December. This oil has a gravity of 18° Bé. The total production for 1928 was 28,841 barrels.

Dinn Gas Pool

The Dinn gas pool, in western Duval County, was opened in 1926 as a gas well by No. 1 Dinn of the Simms Oil Co. Aside from three dry holes drilled near by no further attempt at development in this area was made until the fall of 1928, when the Rio Grande Oil Co. completed its No. 1 Dinn as a 20,000,000 cu. ft. gas well with a 500-lb. reservoir pressure. The producing horizon is a 1770-ft. sand near the Frio-Fayette contact. Structurally this pool is a small eastward pointing nose about 8 miles basinward from the Reynosa escarpment.

Palangana Dome

Although the Palangana and Piedras Pintas salt domes have been known for a good many years and in spite of the fact that Palangana had been quite thoroughly tested for both cap rock and peripheral production, in August the National Oil Co., in drilling No. 1 Schallert for sulfur on top of the dome, found an oil-bearing area in the cap rock at a depth of from 450 to 550 ft. This was completed as a 60-bbl. oil well which produced 1873 bbl. of 14° Bé. oil up to the close of 1928. This is a daily average of 13 bbl. from one well. No additional wells have been drilled to date.

Piedras Pintas

This salt dome, likewise known for many years, produced approximately 150,000 bbl. of 52° Bé. oil during 1926 and 1927 from two wells at 3600 ft. Each additional well drilled resulted in failure and the last attempt, the Humble Oil & Refining Co.'s No. 7 Walsh, was abandoned early in 1928 at 4502 feet.

Simmons City

The Simmons City gas field, 3 miles southeast of Simmons City in western Live Oak County, is a small gas area in which there are several producers from a 1300-ft. sand. During the year three wells were drilled, two of which were abandoned and one, Shipman No. 1 Kolb, completed as a 7,500,000 cu. ft. gas well.

Three Rivers

The Three Rivers field, near a town of the same name in north central Live Oak County, is a small gas field producing from a 450-ft. and a 660-ft. sand. During the year seven wells were drilled, three of which were abandoned and four completed as gas producers. Two of these wells gaged 2,000,000 cu. ft. each from the 660-ft. sand and two others 500,000 cu. ft. each from the 450-ft. sand.

Crowther, Grubstake and Calliham Fields

The Crowther area, a shallow oil field, in northeastern McMullen County, received no new activity during the year.

The Grubstake gas field, on the Live Oak-McMullen County line, was also inactive during the year.

The Calliham field, a shallow pool in eastern McMullen County which has produced some oil, was inactive during 1928.

Mount Lucas Gas Field

The Mount Lucas gas field, including the neighboring gas pools in the vicinity of Mathis in southeastern Live Oak County and western San Patricio County, was fairly quiet during the year. Production comes from a 2100-ft. sand, the wells range up to 40,000,000 cu. ft. of gas and have a reservoir pressure of about 850 pounds.

White Point and Saxet Fields

The old White Point gas field in San Patricio County, on the north side of Nueces Bay, and the Saxet gas field, directly across the bay in Nueces County, experienced vigorous but normal development during the year. While production does not as yet definitely connect these two fields across Nueces Bay it seems evident that they are both on the same structure and production will doubtless be continuous.

Several sands are productive in this area; namely, 1900, 2100, 2300 and 2500 ft. The wells range from 20,000,000 to 40,000,000 cu. ft. of gas with reservoir pressures ranging from 800 to 1100 pounds.

Refugio Field

The Refugio field, near the town of Refugio in Refugio County, is a gas field of several years standing. During August of 1928, the Texas Gas Co.'s No. 1 Clint Heard came in at 3692 ft. as a 150-bbl. oil well, and thus became the discovery oil well of the field. Since then several other wells have been drilled, some of which have been failures. At the close of the year three wells were producing 669 bbl. per day. This field produced 70,592 bbl. during the last five months of the year.

Kingsville

The Kingsville field, 9 miles southeast of Kingsville in Kleberg County, has 12 producing oil wells having a total daily production of approximately 300 bbl. There are three producing gas wells. The productive sands are at 2120, 2250, 2400 and 2930 ft. and are Pliocene and Miocene in age. In 1927 the production was 149,233 bbl. and in 1928 was 157,785 barrels.

During the year 12 wells were drilled but only four were producers. The total production for the year was 159,785 bbl. and the field has produced 355,410 bbl. since its discovery.

Late in December of 1927, the Humble Oil & Refining Co.'s No. 2 Flato, which had been producing an average of 17 bbl. per day for two years from a 2900-ft. sand, began to make about 2700 bbl. of fluid, 50 per cent. oil, after having sanded up. It produced at this rate for over 30 days, then went dead. All efforts to revive it were unsuccessful, and since then has been pumping 10 or 15 bbl. per day. Several other deep wells drilled near by were failures.

Maverick County

The Rycade Oil Corpn. began operations in 1925 on the Chittem ranch, about 18 miles northwest of Eagle Pass in Maverick County. No. 1 Chittem began making gas at 4418 ft. in the Glen Rose formation in December of 1926. The well blew out and some tools were lost in the hole. Drilling was resumed in 1927 and the tools were recovered. The well gaged 7,000,000 cu. ft. of wet gas and 4 bbl. of high-gravity oil, practically pure casinghead gasoline. At 5580 ft. the gas gaged 9,250,000 cu. ft., and at 5600 ft., 39,500,000 cu. ft., and was producing about 40 bbl. of gasoline. It was finally abandoned at 5630 ft. because of lost drill stem.

Chittem No. 2, drilled about 2½ miles away, found an oil show at 2410 ft. near the contact between the Eagle Ford and Buda. It found another interesting show at 5125 to 5130 ft. and was abandoned late in 1928 at 7635 ft. An interesting feature of this well was the finding of 22 ft. of clean, nearly pure salt at 3676 to 3698 ft., which is believed to be in the lower part of the Georgetown.

No. 3 Chittem, an offset to No. 1, was begun in 1928 and at the close of the year was drilling at about 1000 ft.; this will doubtless be a deep test.

On the Sullivan ranch, 4 or 5 miles farther northwestward, the same company has drilled three tests. No. 3 recently got 2,500,000 cu. ft. of wet gas at 5125 ft. in porous Glen Rose limestone.

The Rycade's activity is on a very large southeastward plunging nose.

Wildcat Drilling

Wildcatting has been fairly active throughout the entire area during the year. Some attempts have been made to pick up a continuation of production along a possible trend; others have been made to locate new structures and new producing horizons. Most of these tests have failed. The successful tests have been covered under "New Fields" in the first section of this paper. Some of these wildcats, however, deserve special mention:

The Callighan Land & Pastoral Co., while drilling a water well on its ranch in north central Webb County, encountered a show of 36° Bé. gravity oil at 640 ft. in the Cook Mountain formation. Several other wells were drilled near by but none were completed as commercial wells.

R. V. Hill drilled several wells in Zapata County about midway between the Randado and Charco Redondo fields. Shows of oil have been found in this area in several wells at about 1000 ft. but no commercial production has been obtained.

In Willacy County, about 10 miles southeast of Raymondville, a show of gas was encountered at about 800 ft. while drilling a water well. E. H. East, however, drilled his No. 1 Harding a few feet away to a depth of 1254 ft. without finding any commercial gas.

The Houston Oil Co. drilled its No. 1 Welder-Wood in northeast Duval County to 3484 ft. without finding production. Some years ago several other wells were drilled in this vicinity and are reported to have had shows of both oil and gas.

The Sun Oil Co.'s No. 1 Washburn, southeastern La Salle County, was abandoned at 3917 ft. This well was on a large nose previously determined by diamond core drilling; it started in the lower part of the Fayette (Upper Eocene) and apparently went entirely through the Claiborne (Middle Eocene) section in this area.

Oil Production in the Permian Basin, West Texas and New Mexico

By A. R. Denison,* Fort Worth, Texas

(New York Meeting, February, 1929)

The Permian Basin as it appears in the title of this article refers to three rather widely separated areas of production. It includes what are commonly known as the "Panhandle" fields of the northwest part of Texas; the West Texas fields, in the southwest part of Texas; and the New Mexico fields, in the southeast corner of New Mexico. These three areas are all included in a single province and produce the majority of their oil from limestones or dolomites of Permian age. The manner of accumulation of oil in the three areas is somewhat diverse. In the Panhandle, production is found on the flanks of an enormous structural ridge, the core of which is granite. In southwest Texas and New Mexico oil is produced from both gentle and steep folds and from lenticular areas of porosity.

Production in Texas

During 1927 Texas produced a total of 216,306,000 bbl. of oil of which the Permian Basin contributed 89,797,000 bbl., or 42 per cent. During 1928, Texas produced 255,021,000 bbl. of oil of which the Permian Basin contributed 145,955,000 bbl., or 57 per cent. The increase in total production is entirely due to the West Texas fields. All other districts in Texas declined during the year while the West Texas fields registered an increase of more than 71,000,000 bbl. West Texas daily average production increased from 260,752 bbl. at the beginning of 1928 to a maximum of 406,318 bbl. per day the first week in May. Due to proration agreements, the production was held at a fairly constant level around 340,000 bbl. during the remainder of the year, having 345,660 bbl. the last week in December.

Daily average production of the Panhandle fields decreased from 80,178 bbl. at the beginning of the year to 59,025 bbl. at the close of the year. The combined daily average production of the Panhandle and West Texas fields at the beginning of the year was 341,138 bbl. and at the close of the year was 405,408 barrels.

Fig. 1 gives a comparison of the production in the Permian Basin in relation to the production of the entire state. It is clearly shown that

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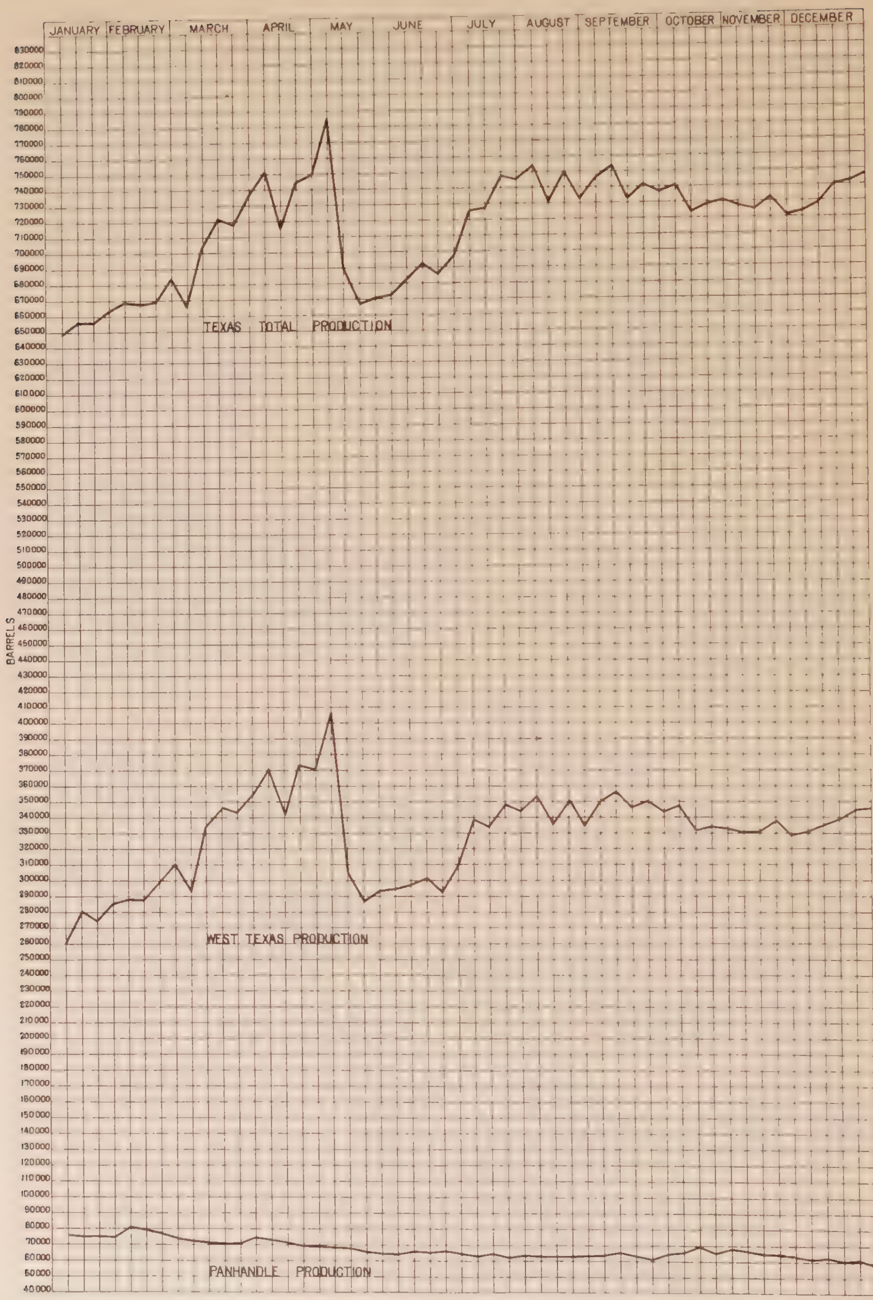

FIG. 1.—COMPARISON OF DAILY AVERAGE PRODUCTION IN THE PANHANDLE FIELDS, WEST TEXAS FIELDS AND THE ENTIRE STATE.

West Texas production controlled the production of the state during the entire year 1928. The sharp drop in the production of West Texas, and therefore in the production of the entire state, in May was due to the placing of the Hendricks pool under proration agreement and reducing its daily average production from 321,982 to 150,000 barrels.

Detailed discussion of development in the Permian Basin is divided into three groups; namely, Panhandle Division, West Texas Division and New Mexico Division.

Panhandle Division

In this division 358 wells were completed, of which 181, or 50 per cent., are oil wells and 91, or 25 per cent., are gas wells. Daily average production at the first of the year was 80,178 bbl. from a total of 1429 wells, or 56 bbl. per well. At the close of the year daily average production was 59,025 bbl. from 1468 wells, or 40 bbl. per well. A total of 25,740,214 bbl. of oil was produced in the Panhandle division. Of this amount Hutchinson County produced 14,853,780 bbl.; Gray County, 7,834,518 bbl.; and Carson County, 2,704,533 bbl. These figures represent a loss of 14,344,466 bbl. The loss in total production largely represents the decline in the producing fields in Hutchinson County, since this county produced less than half as much oil in 1928 as in 1927. A number of new fields were developed during the year but none of these were large enough to increase production or even to halt the general decline.

New Development

Gray County.—Attention was largely focused on Gray County in 1928, on account of the possibilities of securing high-gravity "sweet" oil at considerably less depth than the sulfur oil of Hutchinson and Carson counties. The "sweet" oil production was found in porous granite wash which underlies the dolomite or "Big Lime" section of the older fields. Because of erratic porosity, development of the granite wash pools was featured by wide variations in the initial production of adjacent wells. The most active area in Gray County in 1928 centered at and southeast of Lefors. This development includes the Lefors Townsite pool, the McLarty pool, in sec. 1 and 2, Block 1, A. C. H. & B. Survey, and unnamed pools in sec. 4, 6, and 8, same survey, all of which will probably unite into one productive area as drilling continues. Additional pools opened in Gray County were the Chapman pool in sec. 51, Block 25, H. & G. N. Survey and the Morse pool in sec. 2, Block 26, H. & G. N. Survey. Operations in these pools increased Gray County production to a daily average of 28,856 bbl. for the week ending November 2, a figure only 1800 bbl. less than Hutchinson County, which gave rise to predictions that Gray County would become the premier producing county of the division. However, rapid decline of flush production and decrease

in development due to the limiting of areas of high initial production, dry holes and small wells caused a decrease in the Gray County total to 22,000 bbl. at the end of the year.

Moore County.—The area of Big Lime production was extended into Moore County with the completion of three additional wells on the Armstrong and Byrd ranch. Eight wells drilling at the close of the year indicated that the pool would probably be of small extent with a maximum daily production under 5000 bbl. Development in Moore County is expected to increase in 1929 with most of the wildcatting in the Panhandle confined to that county.

Outstanding Discovery.—The outstanding completion of the year in the division was the Empire Gas & Fuel Co. Dauer No. 1 in the center of the west line of Gray County. This well was completed May 30, 1928 for an initial production of 55 bbl. from granite wash pays at 3010, 3025, 3115 and 3140 ft. This was the first commercial well completed on the south flank of the granite ridge, and opened up a large area for future prospecting. Several wells were started on the south flank following this discovery and the second producer was in process of completion at the close of the year. This was the United 8 Oil Co. Clay No. 1, sec. 177, Block B-2, H. & G. N. Survey, which was completed early in January, 1929 for a 90-bbl. producer from granite wash pay at 3250-51 ft. It is expected that more favorably situated wells will find production on the south flank more nearly in accord with that already developed on the north flank.

Wildcat Drilling.—Wildcat activities outside of producing counties dwindled to the vanishing point during 1928 with the completion of dry holes in Oldham, Sherman, Hartley, Dallam, Hansford and other counties near the producing territory. During 1929 it is expected that virtually all exploratory work will be of a semiwildcat nature in Moore County and along the south flank of the ridge in Carson and Gray counties.

Natural Gas.—The gas area of the Panhandle was not extended during the past year but there was increased activity within the known reserve to make additional gas available for the several trunk lines leading to distant cities. In addition to lines existing the first of the year new lines were constructed south to Midland, Texas and east to Enid, Oklahoma.

Tests by the Bureau of Mines showing that there was a high helium content in some of the Panhandle gas were followed by the construction of a United States Government helium plant at Soncy, 6 miles west of Amarillo. The plant will use gas from the Cliffside area, northwest of Amarillo, which showed the highest helium content of any in the district. The gas is close to the plant on a separate structure not subject to drainage and under lease to one company which has contracted to develop the gas according to the needs of the plant.

Natural Gasoline and Carbon Black.—The natural gasoline industry continued its expansion in the Panhandle with the establishment of new

plants in Hutchinson, Carson and Gray counties. At the close of the year there were 43 casinghead plants in operation having a combined daily gas capacity of 792,000,000 cu. ft. and a gasoline capacity in excess of 422,000 gal. In addition to casinghead plants, three gasoline plants were operating on gas before delivery to domestic pipe lines. These plants have a daily gas capacity of 170,000,000 cu. ft. and a gasoline capacity in excess of 22,000 gallons.

Carbon-black operations were started at the Borger, Lefors, Bowers and Shamrock pools. Nineteen plants were operating or under construction at the close of the year with a combined daily gas capacity of 341,000,000 cubic feet.

Total Production

The Panhandle division from its beginning to Jan. 1, 1929 has produced in excess of 92,000,000 bbl. Of this amount Hutchinson County has produced more than 71,000,000 bbl. Estimates of ultimate recovery from the Panhandle fields were again reduced during the year because of the small size and rapid decline of the newly developed productive areas. An enormous amount of prospective territory remains to be drilled along the north side of the main structural ridge and while the south side of the ridge is not yet proved productive it is expected to develop good oil fields.

West Texas Division

In this division 1258 wells were completed, of which 938 or 74 per cent. were oil wells and 13 or 1 per cent. were gas wells. The oil wells had a total initial production of 5,548,965 bbl., or an average of 5915 bbl. per well. This very high average initial production may represent an exaggerated figure, since the production of the majority of the wells was based on less than 24-hr. gage. At the beginning of the year, 1224 wells were producing 260,753 bbl. per day, or 213 bbl. per well. At the close of the year 1988 wells were producing 338,669 bbl., or 170 bbl. per well. The daily average at the end of the year is principally made up of production limited by proration agreement, the major parts of which are the Hendricks pool, 150,000 bbl., and the Yates pool, 72,500 bbl. This division produced a total of 120,651,932 bbl. in 1928, an increase of 71,-098,481 bbl. over 1927. The comparative yields and percentages of the total are shown in Table 1.

The largest increase in production was in Winkler County (Hendricks pool), which reached its peak during the year. Fig. 2 is an analysis of the development in this division, showing dry holes, oil wells, total completions and new production by months. This chart indicates a peak of completions in August, after which there was a decline until the close of the year. New production follows rather closely the total completions, indicating continuous development of producing areas throughout the year.

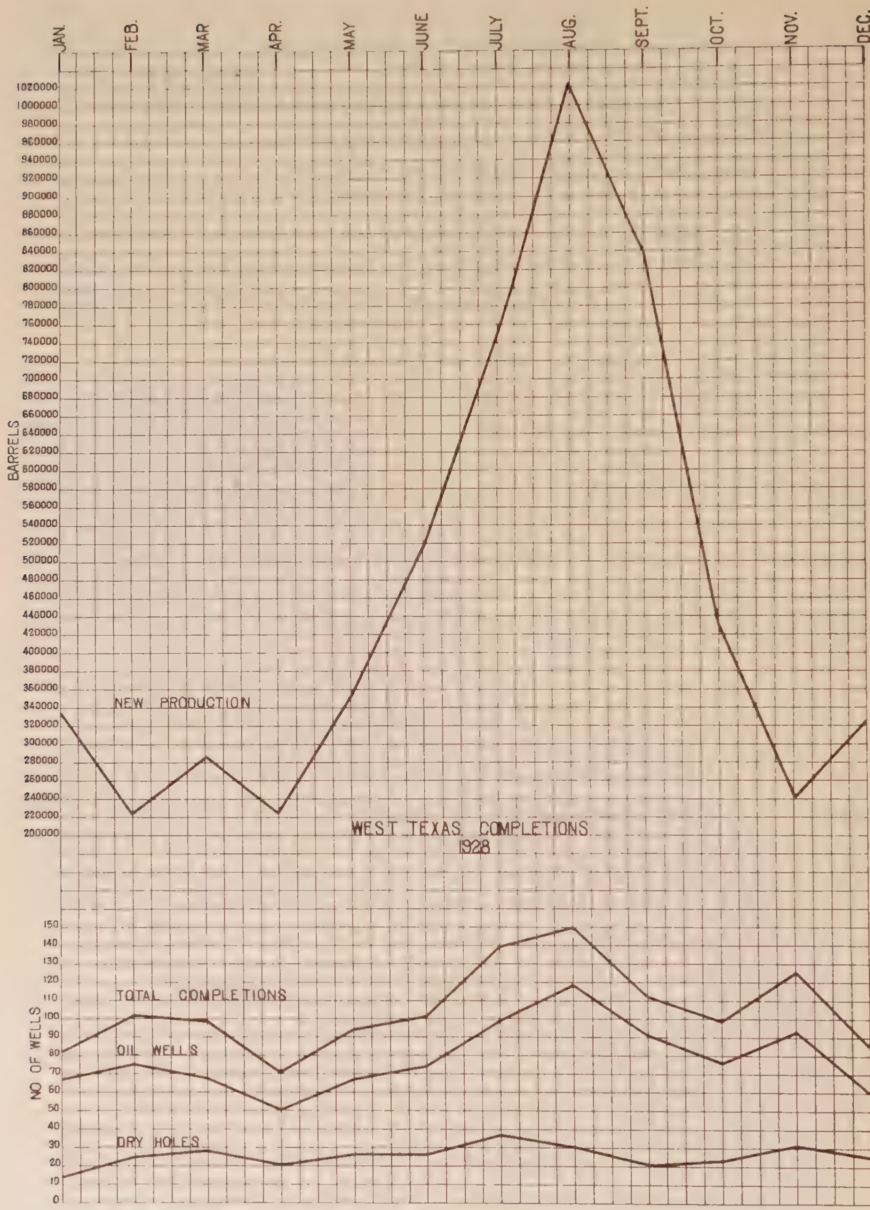

FIG. 2.—ANALYSIS BY MONTHS OF TOTAL COMPLETIONS, OIL WELLS, DRY HOLES AND NEW PRODUCTION IN THE WEST TEXAS DIVISION.

TABLE 1.—*Comparative Yields by Counties*

	1928 Production, Barrels	Per Cent. of Total	1927 Production, Barrels	Per Cent. of Total
Winkler (Hendricks)	58,916,626	48.9	3,109,523	6.4
Crane-Upton (Church-McElroy McCamey)	25,269,757	20.9	29,583,131	59.5
Pecos (Yates)	22,760,385	18.9	5,250,173	10.5
Reagan (Big Lake)	6,993,931	5.8	8,668,381	17.6
Howard-Glasscock (Chalk-Settles)	4,688,929	3.9	1,127,269	2.3
Mitchell (Westbrook-Iatan)	1,084,596	0.89	1,358,280	2.7
Crockett (World)	818,777	0.68	549,486	1.1
Miscellaneous	118,931	0.09	32,904	0.07
	120,651,932	100.06	49,689,657	100.17

New Development

Howard County.—Howard County was favored with two discoveries of major importance. The first was the finding of oil by the Sun Oil Co. in its No. 1 Settles, SE. corner sec. 135, Block 29, W. & N. W. Survey. This well opened a second productive horizon in the Big Lime in the Chalk pool above the original discovery pay found by the Magnolia Petroleum Corpn. ½ mile east of this well in 1927. This new producing horizon was found at a depth of 2395 ft., or about 360 ft. in the lime as compared with 790 ft. for the deeper pay. This well produced 1640 bbl. initial but soon declined to about 500 bbl. By the end of the year seven wells had been completed in this pay, the average initial production of which was 500 bbl. per well. The more important discovery was made on August 4 by the Henshaw (now American-Maracaibo) Oil Co. in sec. 6, Block 32, T.2S. This well flowed at the rate of more than 5000 bbl. per day at a depth of 2248 ft.; it not only brought the largest production yet found in Howard County but also added a new producing horizon at a depth of 200 ft. in the Big Lime. It is regarded by some as an extension to the Chalk-Settles production but since it is coming from a new horizon and is separated by 2½ miles from the nearest producer, it may represent a new field on the same trend with the Chalk-Settles field. At the close of the year, seven wells had been completed in the vicinity of the discovery, none of which made more than 1000 bbl. initial production.

Reagan County.—Reagan County contributed two new productive areas. The first was found by Skelly-Utah Southern Oil Co. No. 1 University, SW. corner sec. 33, Block 8, on January 29. This well was good for 40 bbl. initial from the Big Lime. The top of the pay was 66 ft. below the top of the lime. At the close of the year there were two other producers in this area. All three wells were making a small amount of water and it appears that a large field is improbable. The

second and most important discovery in this county was made by the Texon Oil & Land Co. (group 1) University 1-B, NW. corner sec. 36, Block 9, University land. This well during 1927 found a pay at 6284 ft. which was estimated to be good for 15 to 20 bbl. of 41 gravity oil. On Nov. 30, 1928, this well found another pay at a depth of 8482 ft. At a total depth of 8525 ft. the well began flowing by heads, making 17 bbl. of oil and 86,000 cu. ft. of gas on December 1. Without drilling deeper, both the gas and oil production increased with minor interruptions, so that on December 31 the well produced 1302 bbl. of 52° gravity "sweet" oil and more than 12,000,000 cu. ft. of gas. Both oil and gas have a large gasoline content. Gross production of this well for the first 55 days is 63,873 bbl., or an average of 1161 bbl. per day. This well is the deepest producing well in the world and likewise holds the distinction of being the deepest hole ever drilled. The top of the Big Lime in this well was found at 2780 ft. making a penetration of 5745 ft. Previous to the drilling of this hole, no well in West Texas had penetrated more than 2000 ft. of lime. This well then opens up deeper possibilities throughout the Permian Basin.

Ward County.—Ward County was added to the producing list by the completion of Shipley et al. No. 1 Hazlett, sec. 17, Block 5, H. & T. C. Survey. At a depth of 2481 ft. it began flowing by heads and was later completed for an output of 100 bbl. per day. This well probably does not produce from the regular Big Lime pay and there is some question whether it has reached the Big Lime. The oil is of a slightly higher gravity and slightly lower in sulfur content than the majority of the oil. At the end of the year no other test had been drilled in this vicinity.

Pecos County.—Pecos County had a new producer, which possibly may develop a field, when the Pecos Valley Oil Co. No. 1 Fee, sec. 22, Block 10, H. & G. N. Survey, found oil at 1628 ft. This well was completed for initial production of 185 bbl. of 37° gravity crude on December 6. This oil is likewise of a lower sulfur content than the Big Lime oil and probably is producing from a horizon above the Big Lime. At the end of the year no other tests had been drilled around the discovery.

Winkler County.—Winkler County had two new productive areas during the year. The first was on May 9, when Gibson & Johnson et al. No. 1 Daugherty, sec. 3, Block 74, School Lands, began flowing at an estimated rate of 8000 bbl. per day from the Big Lime at 3168 ft. Water showed up immediately and the well was eventually completed for about 1000 bbl. of pipe-line oil. At the close of the year three other wells had been completed near the producer. One was good for 2000 bbl. of pipe-line oil, while the other two made lesser amounts of oil and water. A pool of unknown size or productivity is indicated in this area. The second discovery was made by Richardson et al. No. 1 O'Brien sec. 50, block F., G. M. M. B. & A. Survey, Sept. 6 at 2805 ft. The well was

drilled below the first oil showing and on October 15 flowed at the rate of 2700 bbl. per day from the regular Big Lime pay at a depth of 2970 ft. It began to make water within a few days after completion and at the close of the year was making about 550 bbl. of pipe-line oil. Early in January, 1929, five additional wells had been completed in the area. Four of these wells were dry holes, two of the dry holes being offsets to the producer. One well three locations north of the discovery was producing at the rate of 700 bbl. per day. A pool seems to be indicated by this well but its size and productivity are questionable.

Miscellaneous.—Wildcat drilling was carried on extensively both in producing and in nonproducing counties. Ward, Pecos, Irion, Howard and Glasscock counties were the leaders, with less activity in Crockett, Loving, Reagan, Terrell, Upton, Borden and Mitchell counties.

Pool Development

The year 1928 saw the intensive development of three pools—Hendricks, Yates and Chalk-Settles. One of these was under proration agreement at the beginning of the year and agreements were reached in both the other areas during the year.

Hendricks Pool

At the beginning of the year the Hendricks pool had 37 wells producing an average of 58,976 bbl. per day with several of the largest wells partially shut in. Development increased and daily production mounted rapidly, so that it was soon apparent that restrictive measures must be applied in order to keep the production within pipe-line and storage limits. An agreement was reached among operators and the Texas Railroad Commission issued an order making 150,000 bbl. the maximum amount of oil to be produced. This order went into effect May 5, 1928, at which time 158 wells were making 321,982 bbl. per day, or an average of 2031 bbl. per well. These figures do not show the true capacity of the field, since many wells were pinched in at the time proration went into effect. Table 2 gives the data concerning the proration of the field during the year.

Table 2.—*Proration Data, Hendricks Pool*

Date	Allowance, Barrels	Number of Wells	Acres under Proration	Potential Production Barrels	Average Potential Production per Well, Barrels
5/5/28	150,000	164	3,150	521,597	3,291
7/1/28	175,000	234	4,560	1,242,348	5,309
10/1/28	150,000	363	6,276	2,496,491	6,877
1/1/29	175,000	468	8,360	2,655,787	5,674

The field had several notable extensions during the year and is now 9 miles north and south by 3 miles east and west. It is limited on the west and possibly on the east, but the north and south limits still remain to be established. The highly prolific area of the field is limited to a strip 1 mile wide on the west side of the field. This strip closely coincides with the steep west dip. The east side has developed large gas wells but small oil production.

Water appeared in the field late in 1927 and this encroachment was a large factor in the agreement to restrict the output of the wells. Beneficial effects resulted from the pinching of the wells but did not entirely retard the water encroachment. More than half of the wells in the field were making water at the close of the year.

The field probably passed its peak during the year, and even though extensions may be made they perhaps will not do more than arrest the normal decline.

Yates Pool

A voluntary agreement among operators was in effect in the Yates pool at the beginning of the year, which limited the production to the pipe-line outlet. At this time 103 wells were producing 48,000 bbl. per day. The agreement led to extensive drilling to prove up additional acreage and a new plan was devised and placed in effect on July 1 by an order of the Texas Railroad Commission. At this time 206 wells were allowed to produce 65,000 bbl. per day. Complete data concerning proration in this field are given in Table 3.

TABLE 3.—*Proration Data, Yates Pool*

Date	Allowance, Barrels	Number of Wells	Acres under Proration	Daily Potential Production, Barrels	Average Potential Production per Well, Barrels
10/1/27	30,000	23		172,845	7,515
11/1/27	37,000	40		313,301	7,842
12/1/27	42,000	71		604,974	8,520
1/1/28	48,000	103		850,000[a]	8,252
5/1/28	52,500	181		1,750,000[a]	9,723
7/1/28	65,000	206	10,000	2,575,047	12,500
9/1/28	72,500	248	13,050	3,425,923	13,814
1/1/29	72,500	284	15,790	4,348,191	15,310

[a] Estimated.

Wells of exceptionally high initial yield are common in this field. All of the gages were based on 1-hr. open flow test and perhaps represent an exaggerated figure. A number of the largest producers, however, showed only a slight drop in production when tested several months after completion, while a few of the smaller wells even showed an increase. Data on three of the largest wells in the field are given in Table 4.

Table 4.—*Production of Wells in Yates Field*

Well	Hourly Gage	Date, 1928	Rate per Day, Barrels
Mid-Kansas-Transcontinental	6,096	Sept. 21	146,318
Yates No. 5-D	5,316	Dec. 31	127,598
Gulf Production Co	5,232	Sept. 21	125,576
Runnels School Land No. 13	4,842	Dec. 31	116,212
California Co	5,195	July 1	124,680
Yates No. 10-A	5,014	Dec. 31	120,337

Tests made late in December, 1928, showed 36 wells with a potential flow in excess of 40,000 bbl. each.

The field is now defined by dry holes or wells with small production. The area under proration, 15,790 acres, probably represents the ultimate productive acreage; since only 284 wells have been drilled the field may be considered as about 20 per cent developed.

Water encroachment was very slow during the year and at the close only 13 per cent. of the producers were showing water, all of which were well down the flanks of the structure. This pool perhaps has reaped great benefits from the restriction of production.

Chalk-Settles Pool

Development of the lime production in the Chalk-Settles pool was very slow because of the lack of pipe-line outlet. No production was run from the lime pay between February 1 and August 1. At the latter date a proration agreement was reached and put into effect by an order of the Texas Railroad Commission. The only restrictive measure that limited the production in this field was the agreement to use neither gas-lift nor swabbing. There is not sufficient gas pressure to cause the wells to flow and the maximum amount that can be pumped from the wells does not exceed the proration allowance. Big Lime production in the pool, as of Jan. 16, 1929, is given in Table 5.

Table 5.—*Big Lime Production, Chalk-Settles Pool*

Pay Horizon, Depth in Feet	Number of Wells	Potential Production, Barrels	Allowance
3000	46	36,206	
2500	11	3,227	
2200	6	6,888	
Totals	63	46,321	27,887

Drilling for "shallow" producing sands above the Big Lime has received considerable development, so that at the end of the year there

were 234 deep and shallow producers averaging 35,725 bbl. per day. This compares with a daily production of 6500 bbl. from 116 producing wells at the beginning of the year.

A large number of proved locations for both "shallow" and Big Lime pays remain to be drilled and much highly prospective semiproved territory remains to be tested.

Recovery Figures

Since discovery of oil in West Texas in March, 1921 to Jan. 1, 1929 more than 190,000,000 bbl. have been recovered from approximately 2000 wells. Of this total more than 120,000,000 bbl. were recovered in 1928. Fig. 3 gives a graphic comparison of the principal fields. Below are given the details concerning per acre and well recovery in the major pools.

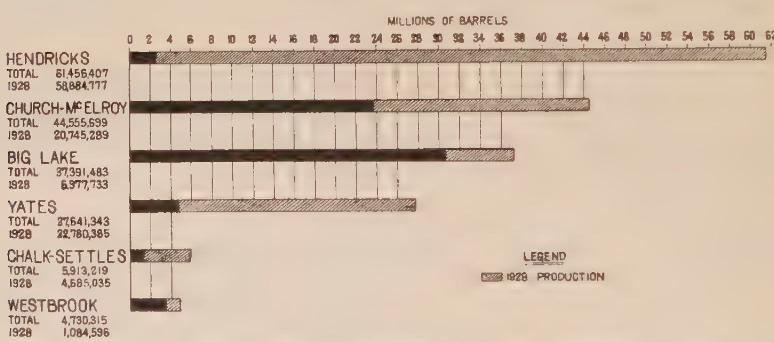

Fig. 3.—Total production since discovery of the principal fields of the West Texas division.

Big Lake Pool

From its discovery in May, 1923 to January 1, 1929 the Big Lake field had recovered a total of 37,391,483 bbl. from 230 wells, an average of 163,876 bbl. per well. The production is from two pays; the upper found at about 2450 ft. is above the Big Lime while the lower found at about 3000 ft. is in the Big Lime. As the entire field is owned by two companies, the development has been slow and it is estimated that 180 proved locations remain to be drilled. The present producing territory is considered to consist of 3360 acres. Using this figure, the field has a per acre recovery of 11,127 bbl. Individual 160-acre tracts which have been completely developed have yielded in excess of 20,000 bbl. per acre. Ultimate production is estimated at between 20,000 and 30,000 bbl. per acre.

Church-McElroy Pool

From its discovery in 1926 to Jan. 1, 1929 the Church-McElroy field has produced 44,555,699 bbl. from 255 wells, or a per well recovery of

174,744 bbl. Assuming that each well is draining from 10 acres, we have a recovery of 17,474 bbl. per acre. The best lease at the date given, from the standpoint of recovery, is the Simms-Atlantic C, E. ½ NW. ¼ sec. 147, which showed 4,212,671 bbl. from 80 acres. This gives a per acre recovery of 52,658 bbl. During December it added 899 bbl. per acre to its total recovery. The north half of this field is now completely defined and drilled up but the south, or McElroy end, still has a large amount of proved but undrilled territory. Ultimate production is estimated between 25,000 and 35,000 bbl. per acre.

Hendricks Pool

From its discovery late in 1926 to Jan. 1, 1929 the Hendricks pool had recovered 61,456,407 bbl. from 498 wells, or an average of 131,319 bbl. per well. Assuming that each well drains from 10 acres, we have an average per acre recovery of 13,131 bbl. Under the existing proration agreement, however, 8360 acres are considered proved. Using this figure, we have a per acre recovery of 7350 bbl. The total allowed production for January, 1929 is 175,000 bbl., which will add 628 bbl. per acre to the recovery figure. The best lease in this pool is the Cranfill & Reynolds Hendricks C, sec. 33, Block 26. This lease, consisting of 20 acres, began producing on March 5, 1928 and had recovered, on Jan. 1, 1929, a total of 2,131,414 bbl. from two wells. This gives a per acre recovery of 106,570 bbl. Several leases in this field have recovered in excess of 20,000 bbl., the majority of which was produced in 1928. Ultimate production is estimated between 15,000 and 25,000 bbl. per acre.

Yates Pool

From the discovery in October, 1926 to Jan. 1, 1929 the Yates pool had recovered a total of 27,641,343 bbl. from 284 wells. This gives a per well recovery of 97,335 bbl. Under the proration agreement in effect Jan. 1, 1929, 15,790 acres are considered proved. Using this figure we have a per acre recovery of 1750 bbl. This figure, however, is misleading, because the field is only partly developed. The per well recovery is rather low, as the runs from the field have been prorated or partly shut in ever since the field was discovered. It is probable that the field may eventually have one well for each 10 acres, which will give a total of 1579 wells. Estimates of ultimate recovery in this field vary from 20,000 to 30,000 bbl. per acre.

New Mexico

Development in the Permian Basin area of New Mexico was largely confined to Lea and Eddy counties. Development in Eddy County was largely adjacent to producing areas. Drilling developed no notable extensions to the already existing fields. Lea County had intensive

wildcat drilling from which several important discoveries resulted. Data concerning these wells are given in Table 6.

TABLE 6.—*Data Concerning Wells in New Mexico*

Well	Location	Date Discov.	Depth, Feet	Date Completed	T. D. ft.	Oil Produced, Barrels	Gas Produced, M. cu. ft.
Empire-State No. 1.......	Sec. 8-21 S.-35 E.	7/16/28	3817	9/21/28	3835	150	
Midwest-State No. 1......	Sec. 9-19 S.-38 E.	5/ 5/28	3180	12/ 6/28	4220	696	
Gypsy-State No. 1........	Sec. 34-21 S.-36 E.	9/30/28	3214	1/17/29	3951		25
Marland-Sholes No. 1.....	Sec. 19-25 S.-37 E.	6/ 2/28	2745	1/24/29	3035		40
Marland-Eaves No. 1.....	Sec. 19-26 S.-37 E.	4/28/28	2905	1/17/29	3000		42
Texas-Cagle No. 1........	Sec. 9-26 S.-37 E.	10/18/28	2836	1/17/29	3474		44
Skelly-Joyner No. 1.......	Sec. 26-25 S.-36 E.	10/30/28	3232	Incomplete		120	
Marland-Lynn No. 1......	Sec. 25-23 S.-36 E.	9/15/28	2847	Incomplete			40
Texas-Shepherd No. 1.....	Sec. 6-26 S.-37E.	10/19/28	2810	Incomplete		50	15

A structural ridge some 30 miles long has been demonstrated by the drilling during 1928. The ridge extends from the southeast corner of Lea County northward. All of the discoveries mentioned in Table 6 are located on or adjacent to this ridge, except the Midwest Refining Co. State No. 1. The ridge is demonstrated as being a large gas reserve, by the four widely separated gas wells along the apparent crest. Oil accumulation with high initial production is expected on the flanks of this structural ridge but drilling so far has developed only small oil wells. At the close of the year there were 24 active wells in Lea County. A number of the wells have been located on the information furnished by the earlier completed wells and the first few months of 1929 should do much toward outlining the possibilities of this large potential reserve.

Gross production from the New Mexico fields decreased 91,063 bbl. in 1928. This was in spite of the addition of several new producers. The comparative production is shown in Table 7.

TABLE 7.—*Production from Oil Fields in New Mexico*

Field	Number of Wells	1928, Barrels	Number of Wells	1927, Barrels
Artesia........................	200	403,377	177	573,573
Maljamar......................	6	69,235	4	38,057
Midwest-State #1..............	1	38,462		
Empire-State 1-B..............	1	9,493		
Totals.......................	208	520,567	181	611,630

SHUT-IN PRODUCTION

While very little production was completely shut in during 1928, the close of the year found three productive areas with limited output. The

daily average production, which might have been reached had no restrictive measures been adopted, cannot be approximated. A potential production in excess of 7,000,000 bbl. daily in the Hendricks, Yates and Chalk-Settles pools is restricted to 302,877 bbl. It is conservative to say that the West Texas fields could have doubled their 1928 production if transportation facilities had been available. Pipe-line, tank-car and local refinery capacity at the beginning of 1929 was well in excess of the daily average production. Pipe lines under construction, to be completed early in 1929, will likewise add to the outlet, hence without restrictive measures West Texas fields could easily flood the market during the current year.

Summary

The Panhandle Division developed several new small productive areas with high initial production but rapid decline. Daily average production declined throughout the year. Casinghead gasoline plants were augmented and carbon-black production was begun. Drilling in 1929 will be largely in semiproved territory, and unless large areas of high initial production are found the total production will be less than 1928.

The West Texas Division in 1928 more than doubled its 1927 production by the development of fields discovered in 1926 and 1927. Several potential productive areas remain to be outlined but no new fields of large extent or high initial production are evident. Due to the proration orders which restricted production in 1928, the fields already developed can produce as much oil in the coming year as in the past year.

The New Mexico Division developed a large highly prospective structural ridge with demonstrated gas reserves and indications of large oil accumulation. It may develop oil fields in 1929 comparable with the largest now known in West Texas.

Production in the Permian Basin will be controlled primarily by oil produced under proration agreement. At the present allowance, 1929 production will not greatly exceed the 1928 total production. It is believed, however, that increases in allowance and new development will combine to give a larger yield in 1929 than in 1928.

Acknowledgment

Acknowledgment is made to John L. Ferguson, of the Amerada Petroleum Corpn., who wrote the paragraphs on New Development in the Panhandle Division, and to others who contributed data and aided in the compilation of the production statistics.

Petroleum Development in North Central and West Central Texas during 1928

By W. G. Wender,* Cisco, Texas

(New York Meeting, February, 1929)

This report covers the area producing from limes and sands of Pennsylvanian age, roughly embracing the territory between the Red River on the north and the Llano Mountains on the south, and between Fort Worth on the east and Abilene on the west. It includes Archer, Cooke, Montague, Wichita, Wilbarger, Clay, Baylor and Foard counties in the North Central Texas or Red River Basin area, and Brown, Callahan Coleman, Comanche, Eastland, Erath, Palo Pinto, Stephens, Shackelford, Throckmorton, Young and Jack counties in the West Central Texas area. Furthermore, it includes a brief review of development in Jones, Runnels, Haskell and Fisher counties.

North Central and West Central Texas during the year 1928 produced an approximate total of 50,948,746[1] bbl. of oil. This represents a decrease of approximately 7,720,250 bbl. under 1927 total production. This decrease was due to a slump in production in Brown, Archer, Wichita, Stephens and Cooke counties. Brown County showed the greatest decrease. The 1928 production in this county was approximately 4,500,000 bbl. less than the 1927 production. Gross production during 1929 in the North and West Central Texas area can be expected to be lower than in the year 1928.

Only one county showed a considerable increase in production. Wilbarger County production increased approximately 3,000,000 bbl. during 1928. Its daily average increased from 9000 bbl. in April to 36,000 bbl. in August. At the close of 1928 it was averaging close to 32,000 bbl. daily.

Drilling activity in North and West Central Texas during 1928 showed but a slight increase in completions. The total number of completions during 1928 was 3902, of which 2094 (53 per cent.) were producers, as compared to 3805 completions and 2112 (56 per cent.) producers during 1927. Brown, Young, Wichita, Archer and Wilbarger counties were the leaders in development.

The outstanding discoveries for the districts were the Consolidated pool, extensions in the Greyback pool of Wilbarger County, and the Stephens pool, Fisher County.

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* Geologist, Amerada Petroleum Corpn.

[1] Does not include production of Jones, Fisher and Runnels counties.

The history of oil development in North and West Central Texas during the year 1928 is briefly reviewed in Table 1 and the following paragraphs.

Brown County

Development in this county centered around the Fry, Crosscut and Blake pools. New discoveries are shown in Table 1.

Gross production to Aug. 1, 1928, from the Fry sand production in the Fry, Smith-Ellis, Byler, Pandem, Buffalo-Clark and White pools totaled 6,723,780 bbl., averaging close to 3000 bbl. per acre from the combined pools. Up to Jan. 1, 1929, the production of the Fry pool proper totaled 4,856,500 bbl., averaging 5750 bbl. per acre. Some individual leases averaged better than 9000 bbl. per acre from date of discovery to Jan. 1, 1929.

Coleman County

Wildcatting in this county during 1928 was quite extensive. Several new oil and gas pools were discovered. The outstanding discoveries are listed in Table 1.

The Jennings pool from date of discovery to Dec. 1, 1928, had an approximate recovery of 700 bbl. per acre. Its present daily production from 25 wells is averaging close to 600 bbl. The average initial production per well in this pool is about 85 barrels.

The possibilities in the Continental-Cheney 2100-ft. pool are still unknown. The discovery well averaged close to 600 bbl. for the first 40 days. However, more recent producers had a much lower initial production. This pool can be expected to be very spotted.

To date but two pools can be considered in the major class in Coleman County. These are the Jennings pool and the Burkett pool. The oil recovery in the Burkett pool up to June 1, 1928, totaled close to 751,000 bbl. The per acre yield averaged about 950 barrels.

Cooke and Montague Counties

No important discoveries were made in these counties during 1928. The production in the Bulcher and Muenster pools of Cooke County is not holding up well. In the Nocona pool of Montague County, considerable drilling took place on inside proved acreage. Production in this pool is holding up well. However, the gravity of the oil is low, and the returns are not high.

Shackelford County

Development in this county centered around the Cook pool. New discoveries are listed in Table 1.

The recovery in the Cook pool up to Dec. 1, 1928, slightly exceeded 5,500,000, bbl., averaging approximately 6450 bbl. per acre. The daily

TABLE 1.—*New Developments in North and West Central Texas*, 1928

Well	Location	Time, 1928	Initial Production, Bbl.	Depth, Ft.	Remarks
	Archer County				
Gohlke No. 1 Wilson	Grayson County School Land Survey, 7 miles south of Holiday	Feb.	50	1550	Discovery well, Gohlke pool.
Continental Oil Co. No. 60 Gose	Sec. 8, S. P. R. R. Survey, 6 miles southwest of Holiday			5280	Reached Bend (Lower Pennsylvania) formations.
	Brown County				
Buffalo-Clark No. 1	Brown County fee land, J. Kinney Survey, 2½ miles east of Fry pool	Feb.	240	1096–1102	Opened Buffalo-Clark pool; Fry sand.
Gilman & McMurray's No. 2 R. Hickman	Thomas Benson Survey, north Brown County	Feb.			Extended Blake pool ¾ mile sand.
Cranfill & Reynolds' No. 1 Eubanks	R. Mitchell Survey No. 141, 3½ miles southeast of Crosscut	April			Opened new pool.
	Callahan County				
Reiter-Foster Oil Corpn. No. 1 P. G. Hatchett	Sec. 24, D. & D. A. Survey, 7 miles southwest of Putnam	Oct.	27	360–365	Opened Hatchett pool; several wells had 60 bbl. initial.
	Coleman County				
E. J. Cunningham et al. No. 1-B Jennings	A. S. Lipscomb Survey No. 94, 7 miles southeast of Santa Anna		75	1172–1177	32° oil; upper Strawn sand.
Continental-Cheney et al. No. 1 Overall	J. Barkley Survey No. 700, 6 miles south of Coleman		700	2109–2118	40° oil; upper Strawn sand.
	Jack County				
Panhandle Oil & Refining Co. No. 1 J. M. Daugherty	J. Hughson Survey, Abstract No. 256, 2 miles northwest of Bryson	April	250	2957–2967	40° oil; sand of Strawn age.
C. Leidecker No. 1 Loving	J. C. Rayston Survey, 3 miles north of Bryson	Nov.	400	3167	40° oil; sand of Strawn age.
	Shackelford County				
Roeser & Pendleton-Marland No. 1-A Cook	Sec. 62, E. T. R. R. Survey, 1 mile north of Cook pool	Feb.	600	1336–1350	Opened new productive area.
Tannehill Oil Co. No 1 Matthews	Southeast corner Sec. 34, E. T. R. R. Survey, 2½ miles northeast of Cook pool	March	370	1140–1155	Opened another Cook sand pool.
	Wichita County				
Holbrook & Woods No. 26 Kemp and Kemper	Block 82, Wichita Falls Farm Lands, south part of county		740	1470–1494	Well deepened; formerly produced at 702, 750, 785, 850, 1200 ft.

Wilbarger County					
Consolidated Oil Co. No. 1 Waggoner	NW ¼ sec. 5, Block 5, H. & T. C. Survey, 5 miles southeast of Greyback pool		1000	1846 1857	Consolidated pool responsible for flush production other than from Greyback pool.
Roxana Petroleum Corpn. No. 1 J. L. Milner	Sec. 30, H. & T. C. Survey, Block 9, Fluhman pool		100	1680–1685	Three pays in Fluhman pool—1450, 1680, 1800 ft.
Fain & McGaha No. 3 W. T. Waggoner	Sec. 50, H. & T. C. Survey, Block 4, 2 miles northeast of Creek Crossing pool	March	60	1288–1295	Opened new area.
Texas Co. No. 1 D. Waggoner	North ½ sec. 43, M. E. P. & P. Survey, Abstract No 491, 2 miles southwest of Consolidated pool	March	135	2356–2375	Opened new pool.
Golding & Cochran No. 1 W. T. Waggoner	Sec. 4, H. & T. C. Survey, Block 17, 4½ miles southwest of Consolidated pool	May	125	1910–1919	
Young County					
Pennell & Cunningham No. 1 J. L. Boone	Northwest corner B. B. B. & C. Survey, Abstract No. 34, 3 miles northwest	Feb.	100	504–515	40° oil; opened Loving shallow pool; several wells had 250 bbl. initial; present productive area about ½ square mile.
Jones County					
Phillips Petroleum Co. No. 1 Joe Winters	SW. corner NW. ¼ sec. 19, Block 19, T. P. R. R. Survey	Sept., 1926	910	2510–2517	Production from Upper Cisco lime; opened Noodle Creek pool. (Note date of this well.)
Hutson & Weaver et al. No. 1 Smith	SW. ¼ sec. 51, Block 18, T. P. R. R. Survey, 4 miles north of Noodle Creek pool	Jan.			Opened new pool.
Huconey Oil & Gas Co. No. 1 Tiner	NE. corner Tiner tract, sec. 14, Block 19, T. P. R. R. Survey	May 28	1500	2512–2522	Opened productive area 1½ miles southwest of Hutson-Weaver pool; Noodle Creek pay line.
Fisher County					
Texas Co. No. 1 Stephens	SW. corner SE. ½ sec. 79, Block 1, H. & T. C. Survey	Sept., 1927	160	3253–3259	Discovery well in county; porous lime pay; 30° oil; productive area similar to Noodle Creek.
Cranfill & Reynolds No. 1 J. A. Young	Center of NE. ¼ of NE. ¼ sec. 208, B. B. B. & C. Survey	April 5	129	3103–3138	Opened new area 3 miles east of Texas-Stephens well; Stephens pay; productive area similar to Noodle Creek.
Haskell County					
Moody Oil Corpn. (now Superior Oil Corpn.) No. 1 Reynolds Cattle Co.	Southeast part of J. Fenner Survey, extreme southeast Haskell County		146	1728–1731	Cisco sand; first commercial oil well in county.

production of the pool was averaging close to 6500 bbl. at the close of 1928.

Wilbarger County

This county led all North Central Texas counties in new development and in important discoveries. The outstanding development in this county took place in the Greyback pool, which was discovered by the Texas Co. in October, 1927. This pool was responsible for most of the flush production in the county. (See Table 1.)

In the Greyback pool to the present date there are two producing sand horizons, encountered at 2350 and 2450 ft. Of these two, the 2450-ft. sand has proved up as the most prolific horizon. Individual wells in the Greyback pool had an initial daily production as high as 4500 bbl. Production in this pool is very prolific, and the recovery should be large.

There are nine different producing horizons in the Rock Creek Crossing pool of Wilbarger County. They are encountered at approximately the following depths: 1800, 1850, 1900, 2100, 2200, 2350, 2420, 2450 and 2550 ft. All of these are sand horizons except the 2550-ft. horizon, which is a porous lime pay, probably Upper Canyon in age. Possibilities exist of finding deeper pay horizons.

The three sands encountered from 1800 to 1900 ft. locally have recovered 13,000 bbl. to the acre. The ultimate total recovery of these three sands can be expected to be above 20,000 bbl. per acre. The 2350-ft. horizon is the most persistent horizon in the Rock Creek Crossing pool. It can be expected to recover around 10,000 bbl. per acre in this pool.

Jones, Runnels, Fisher, and Haskell Counties

Within the last few years these four counties were added to the list of West Texas producing counties. They ought to be grouped into the list of West Central Texas producing counties since they are closely related to them. Production in these counties comes from Cisco and possible Canyon horizons, Pennsylvanian in age. The oil is sweet and has a gravity ranging from 38° to 43° Bé. There is no similarity between the production in these counties and the production in other West Texas counties. (Table 1.)

The gross recovery of the Noodle Creek pool up to Nov. 16, inclusive, was 1,000,249 bbl. of oil. The per acre recovery up to this date totaled 3572 bbl. One individual lease totaled as high as 6758 bbl. per acre.

Both of the productive areas in Fisher County are very similar to the Noodle Creek area. Wells come in from 50 to 1500 bbl. initial. Production holds up very well. Samples of the pay show it to be sandy lime in some wells and porous lime in others. The porosity and water pressure are fairly high in the Stephens pool. Although spotted a long life and

fairly good recovery can be expected of the Fisher County production. Development will be slow, and conservative, since the holdings are large and the drilling cost is high.

Development in Runnels County has been rather discouraging. In the McMillan pool production has been defined by dry holes on the east, south and west. The average daily production from three wells was approximately 175 bbl. at the close of the year 1928. The producing horizon is encountered at 2500 ft. and the age of the pay is Upper Canyon.

Tables 2 and 3 show respectively 1928 production and completions by counties.

TABLE 2.—*Total* 1928 *Production for North Central and West Central Texas Districts*

County	1928, Barrels	1927, Barrels
Archer	7,402,550	10,297,000
Brown	4,503,300	9,093,000
Burkburnett	3,992,500	4,814,000
Callahan	1,363,450	1,628,000
Coleman	978,950	472,000
Cooke-Montague	4,254,550	5,409,000
Eastland-Desdemona	2,781,950	2,755,000
Electra	4,607,600	5,052,000
Fisher	197,532	
Jack	540,150	248,000
Jones	934,864	843,000
Iowa Park-K-M-A	1,180,050	1,211,000
Palo Pinto	160,400	446,000
Shackelford	3,433,850	3,598,000
Stephens	2,750,650	3,289,000
Throckmorton	343,900	884,000
Wilbarger	8,004,950	4,924,000
Young	3,062,400	3,395,000
All others	455,150	311,000
Total	50,948,746	58,669,000

TABLE 3.—*Total* 1928 *Completions by Counties in North Central and West Central Texas Districts*

Counties	Producers	Gas Wells	Dry Holes	Completions	Average I. P. per Well, Barrels
Archer	232		259	491	50
Brown	299	29	279	607	91
Callahan	35	4	28	67	26
Coleman	77	31	146	254	85
Cooke	23	1	27	51	21
Eastland	72	27	107	206	173
Jack	18		46	64	83
Montague	75	6	17	98	27
Palo Pinto	4	7	22	33	29
Shackelford	176	9	103	288	95
Stephens	28	15	40	83	80
Throckmorton	11		24	35	40
Wichita	331		183	514	50
Wilbarger	290	2	82	374	277
Young	248	1	336	585	56
All others	28	15	109	84	17
	1,947	147	1,808	3,902	

Petroleum Development in East Texas and Along the Balcones Fault Zone as Far South as Medina County, 1928*

By D. M. Collingwood,† Dallas, Texas

(New York Meeting, February, 1929)

The year 1928 has been marked by scattered but considerable wildcat drilling considering the overproduction prevalent in the oil industry. This wildcatting has resulted in the discovery of oil in one interior salt dome, several small fields producing from serpentine, Taylor marl, and Austin chalk, and two new fields producing from the Edwards limestone, one of which in the Bruner or Salt Flat area of Caldwell County promises to be of major importance if not quite as large as the Luling field. Fig. 1 shows production by fields for 1928, compared in the case of the older fields, with that for 1927.

New Production From Salt Domes

Boggy Creek Dome

This salt dome was discovered in 1927 by core drilling and deep tests recommended on the evidence of surface geology. A large block of acreage controlled by the Humble Oil & Refining Co. covers the dome. Since the discovery of the deep-lying salt plug and oil on the flank of this dome in 1927, development has proceeded slowly. Since most of the acreage is controlled in a large block by one company there has been no intensive competitive drilling.

Approximately 8 producers and 16 dry holes have been drilled. Production is from the eastern equivalent of the Woodbine and Eagleford horizons of the Mexia district, and has been found extending in a northeast-southwest direction across the River Neches on the southeast flank of the dome. One of the best wells, the T. H. Jones No. 2, had an initial production of 90 bbl. per hr., and others have made from 100 bbl. per day to 50 bbl. per hr., but production of the better wells has either been shut in or choked down to less than 2000 bbl. per day. At the end of the year the daily average production was about 2500 bbl. from 8 wells. Considerable gas pressure is present and one well, the Elliot Clark No. 2, drilled in 1927, was shut in with an estimated wet gas production of over 5,000,000 cubic feet.

* Published with permission of F. H. Lahee, Chief Geologist, Sun Oil Co.

† Sun Oil Co.

Clay Creek Dome

What is believed to be a somewhat deeply buried interior salt dome situated about 10 miles north of Brenham in Washington County was blocked by the Sun Oil Co. on geological field evidence and later checked by geophysical methods and core drilling. The first deep test was

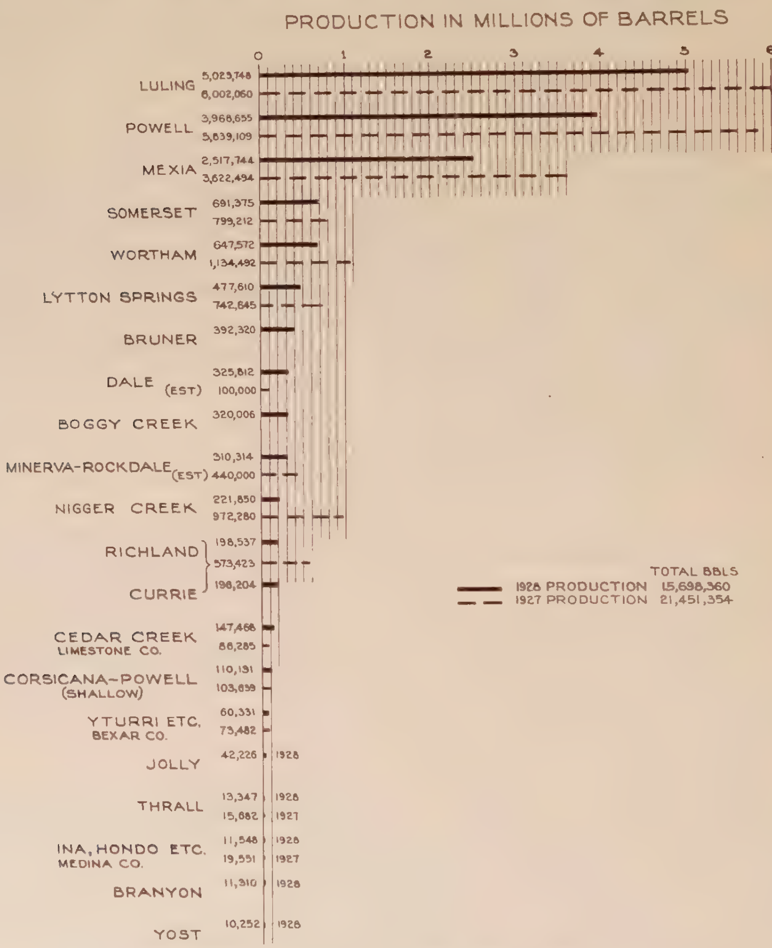

FIG. 1.—PRODUCTION OF FIELDS OF EAST TEXAS ZONE, 1927 AND 1928.

temporarily abandoned dry at 4271 ft. without penetrating salt. The second test, Grote No. 1, was completed as a producer from sand between 1050 and 1155 ft., on Oct. 8, 1928, making 150 bbl. initially. A third well, Grote No. 2, 600 ft. northwest of Grote No. 1, was completed soon after with an initial potential production of 200 bbl. per hr. from sands between 880 and 1390 ft. and was closed in up to the end of the year

while storage and pipe line facilities were being built. Grote No. 1 was then deepened to 1474 ft. and, after plugging back to 1355 ft. to shut off bottom water, had an estimated production of 600 to 1000 bbl. a day. It is expected that these two wells will be opened up for production about Jan. 1, 1929, a pipe line to a loading rack at Gay Hill, 6 miles west, having been completed at the end of the year. Two other wells, one 1100 ft. northeast of Grote No. 1, and one 2200 ft. southwest of Grote No. 2, are drilling around 2000 and 3000 ft., respectively. Two other locations a short distance north and west of Grote No. 2 have been made. No salt has yet been found in any of the wells.

New Production from Taylor Marl and Austin Chalk of Upper Cretaceous

Bruner or Salt Flat Field

In March, 1928, the Bruner et al. (later the Lutex Oil Co.) Davis No. 1, about a mile north of the outskirts of Luling in Caldwell County, found good showings of oil at numerous horizons in the Austin chalk topped at 2428 ft. The well was completed in Chalk at 2683 ft., making initially 30 bbl. a day and later increased to 50 bbl. after a shot. Later the Golden West Oil Co. Wilson No. 1 was brought in flowing over 300 bbl. from the Austin and was the best well from this formation up to the end of the year. These discoveries started a drilling campaign and a number of wells were completed in the Chalk, making from 25 to 200 bbl. a day after shooting.

After discovery of Edwards production in this field in October (see page 432), small production from the Chalk was sacrificed and wells deepened or drilled initially to the Edwards. At the end of the year there were a few wells still producing from the Austin chalk, while a few were producing from both the Austin and the Edwards, where the absence of any water horizon between the two pays permitted this practice. Small production in the Chalk has so far been proved in the southern end of the field, but is very irregular. Small faults east of the main fault, and variable porosity appear to be controlling factors. One or two small wells in the Chalk have also been completed on the west and downthrown side of the main fault. Many shows of oil have been encountered in the chalk where commercial production is not obtained.

Branyon Well

Towards the end of April, 1928, the Texas Co. found good showings of oil in the Austin chalk in its Branyon No. 2. The Chalk was topped at 2075 ft. and drilled to 2240 ft., where a 4-ft. core of Del Rio was obtained. The well was completed at this depth after a test with a Lewis drill-stem tester showed the well good for 200 bbl. a day of 39°

Bé. oil. On May 1 the well, pinched in, made 70 bbl. per hr. Wells to the southwest and northeast have since been drilled but all have been dry holes. As a fault line field, it appears to be limited to only a location or two along the fault, and to be in the nature of a freak well probably in the fault plane. Although no other producing well has yet been drilled, it is possible that the producing area may extend a short distance to the east or south.

Norwood Well

About the middle of December, 1928, the Empire Gas & Fuel Co. Norwood No. 1 found a good showing of oil in 25 ft. of sand and marl near the base of the Taylor of the upper Cretaceous, the total depth being 3779 ft. This well is located near the San Marcas River about 10½ miles northwest of Gonzales in the county of the same name, and not far from the Caldwell-Gonzales County line. A sample of the oil tested 27° Bé. and showed a little B.S. and water. The production was estimated as 500 bbl. after swabbing tests. During the last half of December several heads of oil were made while the well was being rigged with standard equipment for pumping. One offset well has been announced and other wells in the vicinity are expected to be drilled early in 1929.

New Production from Serpentine in Upper Cretaceous

Yost Field

Since the discovery of the Lytton Springs serpentine field in March, 1925, the search for additional masses of productive serpentine has resulted in the discovery of the Dale field, also in Caldwell County, in June, 1927, and the Yost field, about 3 miles southwest of Cedar Creek in Bastrop County, in October, 1928. The Yost No. 1 discovery well of Cranfill & Reynolds and A. M. Loomis, found serpentine from 1488 to 1598 ft. with good showings of oil in the upper part, and was completed with an initial production of about 200 bbl. Shortly before the end of the year there were six producing wells in the field, all but one having initial production of 100 to 300 bbl. The Cranfill & Reynolds Yost No. 3, the next location southeast of the discovery well, had casing set about 5 ft. below the top of the pay, and only made a small well initially, but after deepening from 1418 to 1450 ft. and reaming the hole below the casing seat the well came in flowing 1600 bbl. of pipe line oil a day. The Amerada Yost No. 1, two locations northeast of the discovery well, has been abandoned. This does not quite limit the field in this direction since this well had a showing of oil but could not be brought in as a producer after having set casing through the pay in the top few feet of the serpentine. The field is not yet defined to the south, west, or east. Although an important small field, as a producing unit it is not expected

to have the areal extent of the original Lytton Springs field. At the end of the year the daily production was about 2000 bbl. from 6 wells.

In contrast to the oil of the Lytton Springs field, which has a gravity of 38.5° Bé., the Yost field oil has a gravity of 27° to 30° Bé. Considerable water was found in the lower part of the serpentine in at least one well, while very little, if any water was encountered in the serpentine of the Lytton Springs field. In this connection it is significant to note that the Yost field lies along a main line of the prevailing type of "en echelon" faulting with downthrow to the west which is evident at the surface, while the Lytton Springs field lies between two of these parallel lines of faulting. Some minor faulting in the Austin and older formations is however suspected along the western edge of the Lytton Springs field and here sulfur water was encountered in wells drilled below the serpentine horizon. With a water level high up in the serpentine body of the Yost field it does not appear that the local closure in the lower Taylor sand or domal top of the serpentine body will have permitted extensive accumulation. The field while expected to be small will also probably have a high rate of decline.

Lytton Springs Townsite Well

Shortly before the Yost discovery, a small producer was found in the Lytton Springs Village Townsite, where the Cranfill & Reynolds-Sun Oil Co. Cardwell No. 1 found 21 ft. of serpentine above the Austin chalk from 1504 to 1525 ft. and made an initial production of 25 bbl. Three dry holes have since been drilled a few locations to the north and southeast. The Jarmon et al. City Tabernacle No. 1, 1500 ft. southeast of the producer, found 30 ft. of serpentine which was nonporous and unproductive.

It does not appear likely that a producing area of more than a few locations will be found in this small pool, which is situated on the same major line of faulting as the Yost field, and about 10 miles southwest.

These discoveries have revived interest in the search for serpentine plugs and masses along the major fault line belt through Bastrop, Caldwell and Guadalupe counties. Some wells have found small thicknesses of tight unproductive serpentine. Several wildcats are now drilling or are planned for the near future.

New Production from Edwards Limestone of Comanchean or Lower Cretaceous

Jolly Field

In spite of an extensive drilling campaign along the Mexia-Luling zone of faulting in the past few years, no production had been found in

the Edwards limestone, outside of the Luling field in Caldwell County, until the Roxana Petroleum Corpn. in its Jolly No. 1, 3½ miles west and a little north of Lockhart, got a producing well from the Edwards topped at 1308 ft. in June, 1928. This well had an initial production of 37 bbl. of oil with 200 bbl. of sulfur water, and was located according to surface geological indications on a so-called "back" fault or line of faulting with downthrow to the northwest extending parallel to, but about 8 miles west of the Luling fault. Several more wells were immediately drilled with somewhat higher yields between 50 and 250 bbl. of oil, but more or less sulfur water is produced giving much trouble in treating the oil. At the end of the year the production of the field was about 300 bbl. from 12 wells.

Bruner or Salt Flat Field

In October, 1928, the Sun Oil Co. Malone No. 1, about 1½ miles north of Luling in Caldwell County, was deepened to the Edwards limestone, having failed to get much more than a good showing in the Austin chalk from which earlier wells in this field were producing. A good well was brought in from the Edwards topped at 2712 ft., with an initial production of over 700 bbl. a day. This constituted the second discovery of production in the Edwards limestone for the year, the Jolly field in June, 1928, being the first. This discovery gave added impetus to the drilling campaign in this field and in neighboring areas along fault lines. Wells in the field producing from the Chalk were in most cases drilled deeper to the Edwards. At the end of the year there were 42 wells in the field, including one or two producing from the Chalk with a total daily production of about 10,000 bbl., mostly from the Edwards limestone. There were about 60 derricks in the field with 40 drilling wells. The field is partly defined to the south with dry holes and a steep dip, and being a fault line field, one or two dry holes on the downthrow side have approximately defined the northwestern limits. There remains the northern and eastern extension to be defined. Recent shallow gas blowouts and correlations in drilling wells to the north and east indicate that the field will probably extend as a narrow strip at least 4 miles long. The width of production may in places be more than four or five locations.

Development in Older Fields

Mexia Fault Zone Fields

No new developments of any importance have occurred in the old fault line fields. Practically no new drilling has been done, the fields having been defined, and approximately all desirable inside locations having been drilled previous to 1929. Table 1 shows the approximate age, and the total production, number of producing wells, and decline rates for 1928 of the older fields of the Mexia-Luling fault zone.

TABLE 1.—*Percentage Decline of Production in Older Fields of Mexia-Luling Fault Zone*

Field	Discovery of Field	Number of Wells, January, 1928	Number of Wells, December, 1928	1928 Production, Bbl.	Decline of Daily Average Production per Well for 1928, Per Cent.	Decline of Total Annual Production, 1927–1928, Per Cent.
Powell	January, 1923	739	674	3,968,655	16.9	32.0
Mexia	October, 1920; 150-bbl. well. Summer, 1921; 4000-bbl. well	424	422	2,517,744	21.9	30.5
Wortham	November, 1924	185	166	647,572	20.8	42.9
Nigger Creek	July, 1926	50	38	221,850	39.0	77.2
Richland	February, 1924	64	54	198,537	(7.2)*	31.2
Currie	October, 1921	38	37	196,204	(3.8)*	
Cedar Creek	August, 1927	12	13	147,468	75.4	(70.9)*
Corsicana-Powell (Shallow).	Corsicana, 1895. Powell, 1900			110,131		(6.3)*
Luling	August, 1922	554	579	5,023,748	11.7	16.3
Lytton Springs	March, 1925	304	293	477,610	26.7	35.7

* Per cent. increase.

Production of the heavier crude (30° to 31° Bé.) in the Corsicana-Powell district from the shallower sands in the Navarro-Taylor section of the upper Cretaceous was about 8700 bbl. a day at the end of 1928. Approximately the same amount was being produced at the end of 1927. Some increase in production from inside drilling and cleaning of old wells was sufficient to offset the natural decline of the older wells which, however, is at a very low rate.

Minerva-Rockdale Field

Some development drilling has been done during the year in connection with the gradual extension of the field to the south. A producing area south of Rockdale is now being slowly developed. The estimated decline of 29.5 per cent. in total annual production of the field does not represent the true normal settled decline of the field as some new flush production was brought in.

Luling Field

Some new drilling of inside locations and in extension of the producing areas has been carried on during the year, resulting in the addition of a small proportion of flush production to the settled production of the field. The decline in daily average production per well for the year of 11.7 per cent. is therefore probably slightly low as an index of the normal rate of decline of the settled production. A few wells have been aban-

doned as their operation reached the economic limit. The production at the end of the year was about 13,000 bbl. from 579 wells.

Lytton Springs Field

There was no new drilling in the Lytton Springs field, the limits of production having been defined and inside locations drilled prior to 1928. The percentage decline of production for the year therefore represents the normal rate of decline for the settled production of the field. Eleven wells were abandoned during the year as the economic limit of operation was reached. The production at the end of the year was about 1100 bbl. per day from 293 wells.

Dale Field

The proving up of the Dale field progressed slowly during the year. Production is obtained from serpentine and Taylor sand near the base of the Taylor marl formation of the upper Cretaceous at depths ranging from 1900 to 2250 ft. The field was extended somewhat by the drilling of about 20 close-in wells during the year, the proved area being now about ¾ mile east and west by ½ mile north and south. The limits of the field are closely defined to the west, and at a distance of 2000 ft. from production to the south by dry holes with little or no serpentine present. Dry holes with nonporous serpentine have been found surrounded by producers from porous serpentine in the Lytton Springs field. Two dry holes, therefore, which encountered a thickness of tight serpentine immediately to the north of the proved area cannot be considered as defining the edge of the field in that direction, particularly since there is one small producing well with considerable thickness of serpentine 4500 ft. north of the main producing area. The wells are mostly small, an average initial production being about 75 bbl. There was a peak production of 1157 bbl. per day from 30 wells in April, 1928, while at the end of the year the total daily production was about 700 bbl. from 38 wells.

Somerset Field

Very little new drilling has been done during the year. The decline of production of 7½ per cent. during the year indicates a very slow decline rate and a long life for this old field which has been producing for 15 years from lenticular sands in the Navarro and Taylor formations of the upper Cretaceous.

Other Fields in Bexar and Medina Counties

A small amount of production was obtained from several small fields in Bexar and Medina counties in which no new developments of any importance occurred. At the end of the year the Yturri field in Bexar County was producing about 151 bbl. a day, the total annual production

having declined about 13.5 per cent. from that of the preceding year. Both the Ina and Hondo fields in Medina County were producing about 15 bbl. a day at the end of the year, with an annual decline each of 41 per cent. from the previous year's production.

Exploration

Deep Drilling in Comanchean and Older Rocks

The following tests were important during the year in exploring formations below horizons then producing:

The C. F. Lytle Thompson No. 4 deep test to the Trinity followed several deep tests to the Glenrose drilled along the Mexia fault zone in the previous year, in which gas and small oil shows had been encountered in the Glenrose. The Lytle well, spudded in on April 13, was drilled with an excellent rig and equipment, including the latest improvements in drilling technique and efficiency. Ten-inch casing was cemented at 3857 ft. and the hole was carried to 6002 ft. in excellent condition, where the test was temporarily abandoned on Oct. 14, after coring nearly 300 ft. of Trinity sand section.

The United North & South Kelly No. 1, 2500 ft. west of the northwest end of the Luling field, and the same company's Tiller No. 2, 600 ft. west of production in the middle of the same field, were abandoned early in August at depths of 7859 ft. and 7504 ft., respectively. These tests had been drilling for 3 or 4 years and had been in schist since a depth of about 4700 ft. The Kelly No. 1 was drilled 759 ft. during the last year of drilling, with three tours of five men each, an average of about 2 ft. per day. The Tiller was drilled 930 ft. in the last year. These tests were drilled with rotary tools with 148-ft. derricks. At one time the Kelly at a depth of 7100 ft. was the deepest test ever drilled in Texas, but this depth has since been exceeded by the Texon Oil Land Co. University 1B in Reagan County which is producing from 8525 feet.

Geophysical Methods

The seismograph was used in 1928 to a less extent in the area than in the previous years' intensive exploration campaign for interior salt domes in East Texas.

The torsion balance and magnetometer were used by several companies, the magnetometer also being used by independent operators and consulting geologists. Definite success has been obtained in some cases by following recommendations made on interpretations of magnetic and gravimetric results, but the technique of interpretation into terms of geological conditions of economic significance is only slowly developing by research, investigation and trial, and at the present time does not seem to have achieved its maximum usefulness.

Outlook for 1929

The Luling, Powell and Mexia fields have supplied 11,500,000 bbl. or 73 per cent of the total production in the east Texas area for 1928. By projecting the 1927 to 1928 annual decline rates these fields may be expected to produce about 3,000,000 bbl. less in 1929.

The Bruner field, which was producing about 10,000 bbl. a day at the end of 1928, with about 40 wells drilling, will be drilled up rapidly in 1929, as the acreage is split up into many small holdings, and no cooperative curtailment program is being considered. Under these conditions the field will undoubtedly produce at a much higher figure than 10,000 bbl. a day before reaching its peak, but using this very conservative figure for an average production for 1929 an annual total of nearly 3,750,000 bbl. is to be expected. This will more than offset the expected decline in the Luling, Powell and Mexia fields.

With the exception of the two salt dome fields, Boggy Creek and Clay Creek, there are no indications at present of the other new fields discovered in 1928 being other than small fields, both in quantity of production and areal extent, although of course development may prove larger areas than anticipated. Sufficient new production may reasonably be expected from these small fields to offset the decline in the older smaller fields.

Sufficient production acreage has been proved on the southeast flank of the Boggy Creek Dome, which, if opened up for intensive development, would be capable of producing enough oil to materially swell the production figures for 1929. Since, however, the acreage is controlled principally by one big company there will be no competitive drilling, and probably a very conservative drilling program will be followed.

Should a considerable productive area be proved on the Clay Creek Dome there will also be no danger of an intensive competitive drilling campaign with consequent overproduction and distress oil, since the acreage on this dome is held by one company.

In summing up it appears assured that the area can maintain its present output from resources already proved, but in some cases not being produced intensively. The only threat of an increase of production appears to be in the Bruner field. If cooperative curtailment had been in force from the discovery of this field, the east Texas area would be reasonably assured of its share in the control of production so necessary for the industry at this time of overproduction of crude.

Acknowledgments

The author wishes to thank Francis E. Heath, of the Sun Oil Co., for his cooperation in gathering statistics and preparing this review. He is also indebted to Dr. F. H. Lahee for suggestions and editorial criticism.

Review of the California Oil Industry in 1928

By W. R. Wardner,* Bakersfield, Calif.

(New York Meeting, February, 1929)

During 1928 low prices in the East greatly restricted the Atlantic market for California petroleum. The situation was made difficult by only partial control of production. The month of December is estimated in the figures presented here and it is hoped that the differences in the final figures will be immaterial. Daily averages are used throughout.

Production

Daily average crude production for 1928 was 633,942 bbl., very little more than 1927. Natural gasoline production was 35,453 bbl. daily and the supply (crude and natural gasoline) was 669,395 bbl. However,

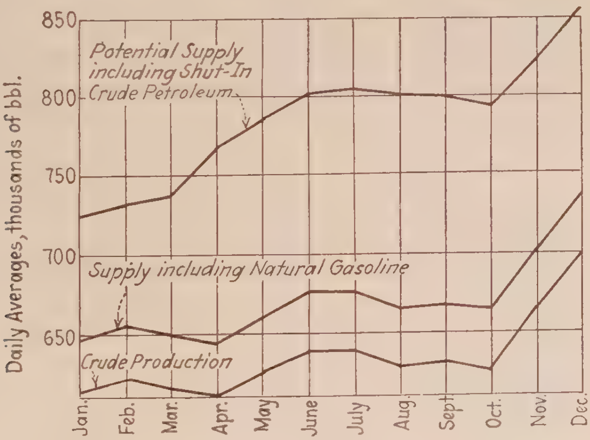

Fig. 1.—California petroleum supply, 1928.

potential supply was 785,621 bbl. daily, 47,436 more than that of 1927. This is accounted for by more production being shut in so that 116,000 bbl. daily was conserved in 1928 which would otherwise have been produced.

Fig. 1 shows production by months for 1928. It will be noticed that while crude production held fairly uniform from January to October, the

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potential supply was increasing. The mounting production from Long Beach was offset in a measure by closing in wells in other fields. In November and December flush production from Santa Fe Springs, added to the prolonged peak at Long Beach, resulted in an abrupt upswing of the curve. December crude production is the highest of the year and is estimated at 697,000 bbl. daily.

There was intensive development of the deep zones at Long Beach and Santa Fe Springs, both closely drilled fields in the Los Angeles Basin. Four new fields were discovered during the year: Elwood, Kettleman Hills, Hawthorne (Lawnsdale) and Fruitvale. Miocene production was also found at a new place in the Midway field. Isolated discoveries and extensions of known pools considerably increased the prospective area contiguous to the Kern River field on the East Side of the San Joaquin Valley.

The Elwood discovery is perhaps the most important of these because it opens up possibilities in such a great territory. Kettleman Hills comes next by reason of its vast area and the very high grade oil obtained.

California had peak production from three fields in 1923, Huntington Beach, Long Beach and Santa Fe Springs. Torrance was the only one in 1924, and at that time many engineers believed that the deluge was over and would not occur again. However, in 1925 there were Dominguez, Inglewood and Rosecrans in flush production; in 1926, Long Beach (Los Cerritos), Ventura Avenue and Huntington Beach Townsite; in 1927, Seal Beach, Richfield and Fullerton; and in 1928, Long Beach Deep Zone and Kern River West Front. Table 1 is a list of fields which could furnish flush production in 1929.

Table 1.—*Possible Flush-production Fields,* 1929

Light Crude	Heavy Crude
Midway-Sunset	Kern River, West Front
Fruitvale	Mount Poso
Kettleman Hills	Round Mountain
Elwood	
Ventura Avenue	
Santa Fe Springs	
Long Beach	
Inglewood	
Seal Beach	
Potrero	
Hawthorne	

It may be, therefore, that the rapid succession of discoveries of new fields and of extensions and deeper sands in old ones is to continue. The remarkable success of geological work helps to bring this about. Each new discovery teaches a lesson that leads to others. Mechanical advancement makes deeper and faster drilling possible. Improved

production methods, such as the gas-lift, result in more rapid extraction of oil and probably in greater ultimate recovery. The old way of waiting patiently for each period of overproduction to pass does not fit present-day conditions. The industry must devise some effective methods of production control.

TABLE 2.—*California Production by Fields*

District	1928*		1927	1926
	Total	Daily Average	Daily Average	Daily Average
Kern River	5,072,331	13,859	16,708	11.941
Mount Poso	52,404	143	110	
Fruitvale	125,664	343		
Round Mountain	45,048	123	24	
McKittrick	1,801,853	4,923	5,084	5,375
Midway-Sunset	27,372,079	74,787	86,769	93,065
Elk Hills	8,130,641	22,214	27,597	33,679
Lost Hills-Belridge	1,524,255	4,164	4,151	4,640
Coalinga	4,660,819	12,734	19,602	19,989
Kettleman Hills	183,000	500		
Wheeler Ridge	330,148	902	1,027	1,019
Watsonville	22,025	60	57	57
Santa Maria	2,049,625	5,600	5,477	5,075
Summerland	44,868	122	136	128
Elwood-Goleta	923,274	2,522	238	
Rincon	1,084,331	2,962	16	
Ventura Avenue	18,961,052	51,806	48,791	40,536
Ventura Newhall	2,097,794	5,731	6,021	6,039
Los Angeles-Salt Lake	564,021	1,541	1,728	1,852
Whittier	611,988	1,672	1,810	2,044
Fullerton (Brea Olinda)	5,774,689	15,778	19,203	19,144
Coyote	4,915,408	13,430	14,101	16,522
Santa Fe Springs	16,021,126	43,773	41,517	47,799
Montebello	4,361,940	11,918	15,064	17,851
Richfield	6,785,583	18,539	21,600	15,272
Huntington Beach	19,688,685	53,794	72,177	52,232
Long Beach	62,434,236	170,585	94,635	103,923
Torrance	6,444,980	17,609	22,846	28,370
Dominguez	4,264,115	11,650	16,131	21,374
Rosecrans	2,366,263	6,465	9,606	16,752
Inglewood	10,765,709	29,414	34,936	47,644
Newport	13,766	37	34	90
Seal Beach	12,430,164	33,962	45,000	1,609
Potrero	84,200	231	2	
Hawthorne	15,700	43		
Total	232,022,784	633,942	632,196	614,019

* December, 1928, estimated.

Table 2 shows the crude production for 1928 by fields; daily averages are compared with 1926 and 1927. Nothing unusual occurred in many of the fields and no comment on them is needed. The outstanding developments are discussed briefly in the following section.

Long Beach

It has been established that deep-zone production is coming from the Upper Miocene instead of the Lower Pliocene as had been supposed. During the year 245 wells have been completed in this zone with an average daily initial production of 1384 bbl. The deepest well in the field is the Shell Co. No. 3 Wells at 8087 ft. The deepest producer is the Shell Co. No. 4 Fee at 7988 for 1730 barrels.

Production began to climb in September, 1927, and a peak was attained Sept. 17, 1928, of 159,000 bbl. daily from the deep zone and 217,000 bbl. for the field. The falling off has been gradual since then. There are 170 wells drilling, as of Dec. 27, and the completions will prevent a rapid decline for some time.

Santa Fe Springs

There were two deep tests drilled during the early development of the field; one to 7212 ft. was off structure, and the other to 6113 ft., is now known to have been on the edge of the new deep zone. This zone, named the Buckbee, was discovered in August, 1928, by a well completed at 5980 ft. for 2500 bbl. of 35-gravity oil. Another zone just under the Meyer was found accidently by a well which blew out and caught fire. After being controlled, it produced 5925 bbl. daily of 32 gravity at 5409 feet.

As development proceeds it appears that the Buckbee zone will not be as extensive as the Meyer but will more nearly correspond to the Bell zone.

The lowermost sands productive at Long Beach have not yet been penetrated at Santa Fe Springs.

The first 38 walls completed in the deep zone averaged 3766 bbl. initial daily production. On Dec. 31, there were more than 200 wells drilling and the pace is fast and furious.

Seal Beach

A number of wells in the Alamitos Townsite part of the field have been drilled into the Miocene formation to depths of 6500 to 6600 ft. Initial productions of from 650 to 1500 bbl. daily have been obtained. There are 50 wells in the Alamitos section that could be deepened. The deep zone has not yet been proved productive in the main part of the field. A moderate drilling campaign is now under way.

Potrero

The Potrero field, filling in the gap between Inglewood and Rosecrans, was discovered in September, 1927. The productive zones occur from 3200 to 5800 ft. Two wells have been completed during the year with 1000-bbl. initial production of 47-gravity oil.

The northwest end of this field will be covered by town lots. As of Jan. 1, 1929, no discovery has been made but two wells are being drilled for this purpose.

The Potrero field will probably resemble Rosecrans which never did more than 26,000 bbl. daily.

Hawthorne (Lawndale)

This new field is located about 3 miles from the ocean between the towns of Inglewood and Redondo Beach. The district has been prospected for 9 years. Gas was found and a number of blowouts occurred. Two unsuccessful wells over 5100 ft. deep were drilled, one of them within a mile of the discovery well which was completed in July, 1928, at 5812 ft. for 195 bbl. of 31-gravity oil. Commercial production was proved by the bringing in of another well in December at 5906 ft. for 1100 bbl. of 33-gravity oil with a penetration of 176 ft. of formation. Wells drilled to this great depth require 6 months for completion.

Ventura Avenue

None of the wells have yet drilled through the lower zone on the apex of the structure. The east and north limits of the field are approximately defined but the western limit has not yet been reached. The south limit has been extended about 500 ft. by a recent completion. The productive area is now over 3 miles long.

The deepest well is the Associated Oil Co. No. 100 Lloyd finished in November at 7957 ft. for 1175 bbl. The wells completed during the year showed an average initial production of 1866 bbl. daily.

Rincon (Seacliff)

The field is located on the Ventura Anticline where it passes into the ocean. Several shallow zones have been developed with only fair production. Wells have been finished at from 3000 to 4000 ft. with an average initial of 570 bbl. daily. The producing wells averaged 188 bbl. in November, 1928.

A deep test is being drilled and the future of the field depends on the result.

Elwood

This new field is located about 12 miles north of Santa Barbara on a terrace overlooking the ocean. The discovery well was completed in August, 1928, at 3212 ft. for 3000 bbl. of 38-gravity oil. Other wells have been brought in since with even larger initial yields.

Production is obtained from the Vaqueros sandstones, which are supposed to be about 350 ft. thick. The limits of the on shore area have not been defined. As part of the structure is in the ocean, wells near the shore will be long-lived having a greater drainage.

This is a very significant discovery and will result in testing many known similar structures which have heretofore been considered unsuited for accumulation of oil. Consequently a large area will be opened up for prospecting.

Kettleman Hills

This field consists of three separate domes, north, middle, and south, with intervening saddles extending about 40 miles from Coalinga to Lost Hills in the San Joaquin Valley. The prospective area is very great.

Wildcatting has been under way since 1906. Early wells were less than 1200 ft. deep and no showings were found. Later ones drilled to 3300 to 3500 ft. located sands from which small production might be expected. More recently two wells reached 5680 and 6755 ft. with good showings in the deeper one but commercial production was not obtained.

The discovery well on the north dome was first drilled to 7236 ft. and in October, 1928, while redrilling at 7108 ft., blew in as a wet gasser doing about 40,000,000 cu. ft. and an unknown amount of light oil. The well is cased to 6317 ft., with about 800 ft. of open hole. After being brought under control the well made 4000 bbl. daily of 60.5-gravity oil testing 93 per cent. gasoline. The gas tests 4 gal. per M cu. ft. This is the highest gravity oil ever found in California.

Extensive development is now under way. There is a vast area to be tested but at great depth, so there is no immediate danger of large flush production.

Midway-Sunset

The Republic Oil Co. completed a well during March in the Miocene shales at a depth of 2704 ft. for 1061 bbl. of 22-gravity oil. This is in a part of the field with small shallow production of heavy oil. Other wells drilled since in the vicinity came in with equally good production.

These wells are on, or near, the Midway Anticline. In this connection it is of interest to recall the Obispo well on the Thirty-five Anticline brought in several years ago with large flow from the Miocene shales. Adjacent wells drilled to the same zone were unsuccessful.

These occurrences suggest the possibility of other small accumulations at structurally favorable points throughout the Midway-Sunset fields.

Kern River

The wells completed on the Kern Front during the year averaged 180 bbl. daily initial production. About 4400 bbl. daily production in the old part of the field has been shut in for several years and 9500 bbl. additional is closed in on the Kern Front. This is all heavy oil.

Round Mountain

During the year 12 wells were completed with an average initial production of 425 bbl. daily, mostly heavy oil. There is no pipe line connection and the wells are shut in.

Mount Poso

Development continues over a large area and oil has been discovered north and southeast of the main field. Twenty-two wells have been completed during the year with an average initial production of 344 bbl. daily of low-gravity oil. All wells are shut in.

Fruitvale and Union Avenue

The Fruitvale field is located about 2 miles west of Bakersfield. The first wells produced 22-gravity oil at 175-bbl. rate. Later completions came in with greater initials, one for 2460 bbl. and another 750 bbl., depths from 3600 to 3920 ft. It is reported that production is coming from the Etchegoin (Upper Pliocene).

Union Avenue is a prospective field just south of Bakersfield, as yet unproved. Five wells have been drilled, one of them to 5640 ft. Two of the wells had encouraging showings of 24-gravity oil at about 4400 ft., with a large amount of gas. Obstacles to sustained production have yet to be overcome.

Buttonwillow Gas Field

This area is about 7 miles west of Buttonwillow in the San Joaquin Valley. Seven gas wells have been completed with an estimated capacity of 50,000,000 cu. ft., based on flow tests. Separate zones are found between 2500 and 4600 feet.

Table 3 shows the shut-in production for the various fields as of December.

TABLE 3.—*Daily Average Shut-in Crude Production, December*, 1928

Field	Refinable Crude, Bbl.	Heavy Crude, Bbl.	Total Crude, Bbl.
Kern River		13,820	13,820
Mount Poso		13,750	13,750
Round Mountain		7,400	7,400
Elk Hills	14,450		14,450
Lost Hills-Belridge	1,550	3,095	4,645
Midway-Sunset	288	20,085	20,375
Coalinga	17,650	6,420	25,070
Santa Maria		6,775	6,775
Ventura Avenue	3,200		3,200
Coyote	2,000		2,000
Fullerton (Brea Olinda)	7,900		7,900
Inglewood	900		900
Total	47,938	71,345	119,283

NATURAL GASOLINE

An average of 135 plants reported to the Bureau of Mines during the year. Table 4 compares results with previous years.

TABLE 4.—*Natural Gasoline Statistics*, 1925–1928

Year	Number of Plants Operating	M. Cu. Ft., Treated Daily	Gasoline Produced Daily, Bbl.	Recovery, Gal. Per M. Cu. Ft.
1925	144	648,490	19,777	1.281
1926	146	776,953	25,399	1.369
1927	143	920,806	31,947	1.457
1928	135	1,005,000	35,453	1.480

PIPE LINES

Short oil lines were built during 1928, as follows: Six miles from Rincon to Ventura Avenue; 10 miles from Mount Poso to Kern River West Front; 33 miles from Kettleman Hills to Lost Hills; 18 miles from Elwood to Gaviota. There were many extensions made of gathering lines for both oil and gas. New lines for transportation of natural gasoline from field plants to refineries have been installed.

A large gas line is projected from Buttonwillow and Kettleman Hills to supply the larger towns in the San Joaquin Valley, San Francisco and the Bay cities. This will have an important bearing on the future consumption of fuel oil when the lines are completed and placed in operation.

Refineries

The daily capacity of refineries increased 44,000 bbl. during 1928. Table 5 shows the utilization of crude and some refinery results.

Table 5.—*Refinery Statistics*, 1928

Crude Oil and Products	Percentage	Daily Average, Bbl.	Daily Average, Bbl.
Crude production, all gravities			633,900
Drawn from refinable crude stocks			6,700
			640,600
Crude shipments to Pacific and Atlantic ports		22,000	
Used as fuel or added to heavy stocks		39,100	
			61,100
Crude run to stills	100		579,500
Refined fuel oil output	63		366,000
Refined gasoline and engine distillate	22	126,600	
Cracked gasoline	3	19,500	
Natural gasoline		35,500	
Total motor fuel production			181,600

The exact figures of production of refinable crude are not available but it seems that such production, except shipments, was put through the refineries and the straight-run gasoline extracted, along with enough other products to supply demand. The balance is called fuel oil; part is sold and the rest run to storage. This method has resulted in reducing stocks of refinable crude from 44,000,000 bbl. of March 31, 1926, to 16,500,000 bbl. on Nov. 30, 1928. The stock of heavy crude and fuel oil, about 100,000,000 bbl., is the only considerable reserve for future gasoline requirements should current production ever be insufficient.

Texas-Louisiana Gulf Coast Operations during 1928

By W. F. Bowman* and J. M. Vetter,* Houston, Texas

(New York Meeting, February, 1929)

The Gulf Coast area of Texas and Louisiana produced a total of 47,070,650 bbl. of oil during 1928, a decrease of 7,401,173 bbl. from the previous year. Of this amount Texas produced 39,353,950 bbl., or a decrease of 9,689,296 bbl. from the 1927 output. The Louisiana Gulf Coast produced 7,716,700 bbl., which is an increase of 2,288,123 bbl. over 1927.

The decrease in the Texas Coastal area is due principally to the decline at Spindletop. Production at the beginning of the year in this field averaged 53,400 bbl. daily. At the end it had declined to 35,850 bbl. The increase in Louisiana was due to development in new fields at Kelso Bayou (East Hackberry), Sulphur, Sweet Lake, Bayou Boullion and Sorrento. This production was maintained by the drilling of 984 wells. Of this number 736 were located in Texas and 248 in Louisiana. Of the 984 wells drilled, 571 were reported as producers. Distribution of the various completions is listed in the accompanying tables compiled by *Oil Weekly.*

New Developments

New developments of particular importance in Texas were the finding of a 5000-bbl. well in formations of Cook Mountain age in the Clay Creek field located in northern Washington County by the Sun Oil Co.; the discovery of oil at Dewalt in Fort Bend County by the Humble Oil & Refining Co.; the development of commercial production at Raccoon Bend in Austin County by the same company; and the finding of oil in formations of Oligocene age in the Refugio gas field of Refugio County. The most important development in Louisiana was the finding of oil at Sorrento, east of the Mississippi River, by the Gulf Production Co. The importance connected with these finds is not so great in that they opened up new fields, but in the new territories which they open as possibly productive of oil. Eastern Louisiana has been looked upon with considerable doubt on account of the theory which has prevailed among most geologists that the nature of the formations was not such as to produce oil. The actual finding of oil in that area upsets this theory and

* Consulting Geologists, Bowman & Vetter.

TABLE 1.—*Texas Gulf Coast*

Field	Completions	Producers	Gas Wells	Failures	Initial Production, Bbl.	Annual Production, Bbl.
Barbers Hill	2	1		1	3,100	322,950
Batson	39	32		7	704	498,550
Big Creek	23	18		5	10,560	834,250
Blue Ridge	108	81		27	57,677	2,302,300
Boling	9	5		4	1,392	828,400
Damon Mound						363,150
Goose Creek	32	24		8	2,025	2,551,950
High Island	15	9		6	3,970	*
Hull	65	49	2	14	20,320	4,167,200
Humble	1	1			1,100	683,150
Nash	3	3			3,490	*
Orange	47	33		14	9,042	1,466,100
Orchard						*
Pierce Junction	80	56	1	23	56,111	3,980,400
Raccoon Bend	2	1		1	800	23,650
Refugio	2	1		1	160	*
Saratoga	22	15		7	489	383,400
Sour Lake	30	20		10	797	1,235,350
South Liberty	36	34		2	16,363	1,437,650
Spindle top	46	29		17	20,709	14,021,300
De Walt	2	2			4,000	252,550
West Columbia	5	5			1,570	2,946,200
Wildcats	166	31	5	130	25,154	*
Others						1,055,450
Totals	736	451	8	277	269,533	39,353,950

* Included with "others."

TABLE 2.—*Louisiana Gulf Coast*

Field	Completions	Producers	Gas Wells	Failures	Initial Production, Bbl.	Annual Production, Bbl.
Bayou Boullion	8	4		4	4,320	217,600
East Hackberry	18	9		9	9,176	1,176,600
Edgerly	23	15		8	962	422,850
Evangeline	34	22		12	1,936	373,900
Lockport	23	18		5	7,235	1,489,450
Starks	3	1		2	2,500	*
Sorrento	3	1		2	1,300	282,200
Sulphur	5	3		2	5,680	843,050
Sweet Lake	2			2		659,300
Vinton	33	23		10	1,637	1,642,500
Wildcats	96	24		72	33,353	*
Others						609,250
Total	248	120		128	67,799	7,716,700

* Included with "others."

opens up possibilities which may extend into Mississippi, Alabama, and possibly across Georgia into Florida.

Heretofore large oil wells have never been developed in the Cook Mountain and the overlying Yegua formations. Although a limited amount of oil has been produced from these formations over extensive areas, much doubt has existed as to the limit of their possibilities. The finding of a 5000-bbl. well in northern Washington County dispels that doubt and causes many operators to look with favor upon areas where the Cook Mountain and Yegua formations occur within reach of the drill.

The discovery of oil at Dewalt is of importance in that the accumulation is caused by the arching of beds over a deep-seated salt dome which was located by torsion balance. The favorable results obtained by the Humble Oil & Refining Co. in their development program in this field have directed the interests of the oil industry to a search for similar deep-seated domes. Earlier geophysical work failed to detect this structure, hence there has been a general reworking of areas where irregularities were first noted.

The finding of a new field at Raccoon Bend started a new play along the contact of the Lafayette, or Reynosa formations with the underlying Fleming, or Lagarto clays. As this field was marked at the surface by an inlier of Lagarto clays protruding through the Lafayette sands, a search for similar conditions was started. In this field the oil is found in formations of Jackson age. While this is not entirely new it points to further possibilities for potential reserves.

On account of the large amount of gas which has been developed and the small number of oil wells completed in the southern Gulf Coast of Texas, that territory has been considered unfavorable for oil production. The discovery of oil in the Refugio gas field in formations of the same age as those producing around salt domes has thrown a different aspect on that territory, and caused extensive leasing activities.

Thus the development of oil in eastern Louisiana and southern Texas opens the whole coastal area of the Gulf of Mexico as a possible oil-productive area. The finding of a large oil well in sands of Cook Mountain age in northern Washington County, together with an oil field at Raccoon Bend in Austin County, points to new possibilities over a large area along the inner margin of the Gulf Coast area.

Developments in Texas of lesser importance that have aroused the interest of operators were the proving of new areas on the north end of the South Liberty-Dayton salt dome in Liberty County by the Texas Co.; on the east flank of Barbers Hill in Chambers County by Mills Bennett; on the northwest flank of High Island in Galveston County by Marrs McLean; and along the northeast sector of Pierce Junction, Harris County, by independent operators. The Schoolfield O'Byrne pool in northern Duval County, and new gas areas in western Nueces,

FIG. 1.—LOUISIANA GULF COAST.

northern Bee, and northwestern Victoria counties were also opened up during the year.

Developments of importance in Louisiana, aside from the finding of oil at Sorrento, were the opening of new pools at Kelso Bayou (East Hackberry) by the Calcasieu Oil Co. operating in conjunction with the Union Sulphur Co. and the Magnolia Petroleum Corpn.; at Sulphur by the Union Sulphur Co., and at Bayou Boullion by the Rycade Oil Corpn. The Pure Oil Co. operations at Sweet Lake were rather extensive. A number of tests were drilled at Jennings but without appreciable success.

Geophysics and New Salt Domes

Because of the secrecy maintained by the companies engaged in geophysical prospecting there is not a great deal of information available as to advancements along this line during the year. Apparently there was a tendency among operators to favor the seismograph in prospecting for shallow domes or domes that come within about 2500 ft. of the surface, while the torsion balance seems to be favored in prospecting for deep-seated domes and for outlining the shallow domes. Extensive

Fig. 2.—Texas Gulf Coast.

geophysical exploration work was continued during the year with the result that 12 new domes or structures were reported in Texas and 22 in Louisiana, as listed in Tables 3 and 4 and shown in Figs. 1 and 2.

TABLE 3.—*New Domes or Structures Reported in Texas*

Name	Location (County)	Owner (Company)	Development
Terry	Southwestern Orange	Texas & Gulf	None
Spear	Northwestern Orange	Sun	None
Arriola	Southeastern Hardin	Gulf	None
Hankamer	North Central Chambers	Gulf	None
Smith's Point	Southwestern Chambers	Gulf	None
Strang	Southeastern Harris	Humble & Gulf	None
Genoa	Southeastern Harris	H. C. Cockburn et al.	None
Mykawa	Southeastern Harris	Humble & Cockburn	One well drilling
Aldine	North Central Harris	Humble & Gulf	None
Needville	Southwestern Fort Bend	Myer & SoRelle	One well drilling
Sheppard Mott	Southern Matagorda	H. C. Cockburn et al.	One well drilling
Louise	Central Wharton	Pure Oil	None

The majority of these domes have not been proved by drilling, but development on a number of the Louisiana domes is assured by a trade between the Texas Co. and the Louisiana Land & Exploration Co. In this trade the former agrees to drill at least four wells on each of nine domes discovered and owned by the latter company.

REFINERY AND PIPE LINES

During the year the Shell Petroleum Corpn. began the construction of a 30,000 bbl. refinery on the Houston Ship Channel at Deer Park, in Harris County, Texas. It is expected that this will be completed during 1929. Rail connections and loading facilities on the Ship Channel have been completed. Pipe for 450 miles of 10-in. line has been ordered to connect this refinery with West Texas fields. The Humble Oil & Refining Co. also completed a 15,000-bbl. refinery at Ingleside in San Patricio County.

The Texas Co. and the Atlantic Oil Producing Co. each completed the construction of pipe lines from West Texas into the area. The Atlantic line extends to its loading terminals at Alreco a few miles south of Beaumont on the Ship Channel. The Texas Co. line extends to its refinery at Port Arthur. The Humble Oil & Refining Co. constructed 30 miles of 8-in. lines from the Raccoon Bend field to connect with its North Texas line at Satsuma, and about 20 miles of line from De Walt Dome to connect with its line at Pierce Junction. The Sun Co. built

TABLE 4.—*New Domes or Structures Reported in Louisiana*

Name	Location (Parish)	Owner (Company)	Development
Black Bayou	Cameron T-12-S, R-12-W	Shell	Five wells; cap rock 880 ft.
Lake Misere	Cameron T-13-S, R-5-W	Pure	None
Mallard Bay	Cameron T-12-S, R-3-W	Shell	None
Roanoke	Jefferson Davis T-9-S, R-4-W	Vacuum	One well drilling
Egan	Acadia T-9-S, R-2-W	Gulf and Calcasieu	One well drilling
Vermillion Bay	Iberia T-16-S, R-5-E	Louisiana Land & Exploration	Three wells; cap rock 790 ft.
Caillou Island	Terrebonne T-21-S, R- 14-E	Louisiana Land & Exploration	None
Calillou Lake	Terrebonne T-21-S, R-15-E	Louisiana Land & Exploration	None
Bayou St. Elaine	Terrebonne T-22-S, R-18-E	Louisiana Land & Exploration	None
Pelta Bay	Terrebonne T-23-S, R-18-E	Louisiana Land & Exploration	None
Lake Barre	Terrebonne T-21-S, R-19-E	Louisiana Land & Exploration	None
Timbalier	Terrebonne T-23-S, R-20-E	Louisiana Land & Exploration	None
Lake Netherland	St. Charles T-15-S, R-22-E	Gulf	None
Lake Lery	St. Bernard T-15-S, R-14-E	Gulf	None
Bayou La Fourche	La Fourche T-23-S, R-23-E	Louisiana Land & Exploration	None
Lake Hermitage	Plaquemines T-18-S, R-25-E	Gulf and Humble	None
Bay Batiste	Plaquemines T-19-S, R-25-E	Gulf and Humble	None
Bayou Long	Plaquemines T-20-S, R-26-E	Gulf	None
Home Place	Plaquemines T-18-S, R-15-E Extending across Mississippi River	Gulf and Humble	None
Spanish Pass	Plaquemines T-21-S, R-30-E	Gulf and Humble	None
Quarantine	Plaquemines T-21-S, R-32-E	Gulf and Humble	None
Delta	Plaquemines T-23-S, R-33-E	Texas	None

6 miles of 4-in. line from their new field in northern Washington County to the railroad at Gay Hill. The Moody-Seagraves interest are building a gas line to Barbers Hill in Chambers County to furnish fuel for drilling operations in that field.

SULFUR DEVELOPMENTS

The outstanding feature in sulfur developments during 1928 was the exploratory work and installation of machinery by the Texas-Gulf Sulfur Co. at Boling in Wharton County, Texas. This is generally

believed to be one of the largest sulfur deposits in the world. The machinery installed consists of a battery of boilers with a nominal rating of 7500 hp., designed so that this capacity can be doubled if desired. As accessory to this plant the company has established machine shops, warehouses, offices and about 250 dwellings for employes. A railroad has been constructed to connect the plant with the Southern Pacific Lines.

The usual sulfur operations have been continued by the Texas-Gulf Sulphur Co. at Gulf, Matagorda County, Texas; by the Freeport Sulphur Co. at Hoskins Mound and Bryan Heights, Brazoria County, Texas. At Palangana in Duval County, Texas, the Duval Sulphur Co. completed the erection of a 1200-hp. battery unit which began operations in November. Since that time it is reported to have been producing about 10 tons per hr. from two wells. Ten other wells are ready for operations. This deposit occurs at a depth of about 400 ft. About 2½ miles of railroad is projected to connect with the Texas-Mexican Railway to Corpus Christi.

Petroleum Development and Production in the Rocky Mountain Region during 1928

By Dean E. Winchester* and C. D. Johnson,† Denver, Colo.

(New York Meeting, February, 1929)

The so-called Rocky Mountain region is here made to include Colorado, Idaho, Montana, northern New Mexico, Utah and Wyoming, an area of great distances and relatively sparse population. Conditions of distance, transportation and markets have had their retarding influence on devolopment and production but the increase in facilities and markets in recent years has provided additional incentive for more thorough search for new productive areas and the more complete development of the known fields. The low prices of crude during the past year have offset, to a certain extent, the desire for increased production and much of the effort has been directed therefore to outlining new areas rather than to attempts to increase production from known fields and thereby add to the already sufficient supply above ground.

During the year just closed the Rocky Mountain region has seen consistent efforts to outline new areas and these efforts have been reasonably successful. In this area a very large part of the land is government property, and by cooperation between the government, the private owner and the company it has been possible to carry on development in a scientific manner, providing for the maximum recovery of valuable products at least cost and at times when prices were best.

Due to the fact that in the Rocky Mountain region costs of exploration and development are relatively high because of natural circumstances, it has been the policy of operators to drill test wells only on structures where they controlled a large proportion of the land. Even community lease programs have been effected in certain areas, thus obviating the necessity of offset drilling and the attendant uneconomical and even wasteful production.

Oil production in the Rocky Mountain states has shown a slight increase during the year, the average daily production for November being 78,124 bbl. as against an average in January of 76,681 bbl. The total production during the first 11 months of the year, according to the U. S. Bureau of Mines, was as follows:

* Consulting Geologist.

† Petroleum Geologist.

	Barrels
Colorado	2,514,000
Northern New Mexico	1,970,000
Montana	3,579,000
Wyoming	19,782,000
Total	27,845,000

Increased handling facilities provided during the year include the completion and initiation of construction of several new pipe lines for both oil and gas.

Colorado.—Completion of the 20-in. gas line to bring gas from the Texas Panhandle to Pueblo and Denver. Completion of a 4-in. oil line 19 miles long from the Iles Dome to the railroad at Craig by the Midwest Refining Co. Completion of a small oil line from the Iles to the Moffat field by the Texas Co., to connect there with their own line to Craig.

Montana.—A 12-in. line is under construction to carry gas from the Baker district in southeastern Montana to the large cities of the Black Hills district in South Dakota, 175 miles away. A second gas line is completed from this same area to towns to the east in North Dakota. A 6-mile oil line now also connects the Pondera field in Sweetgrass county with the railroad at Conrad.

New Mexico.—A gas line is under construction to carry gas from the Ute Pasture wells in San Juan Co. to Durango, Colo.

Wyoming.—The Midwest Refining Co. this year began the operation of its 4-in. oil line from the Labarge field to Opal on the Union Pacific R. R., 38 miles away. An oil line connecting the Oregon Basin field with the railroad at Cody was also put in operation. During the closing days of the year arrangements were completed for the construction of a gas line from the Hiawatha Dome, Colo., and the Baxter Basin field, just over the line in Wyoming, to Salt Lake City, Utah. This line will be started early in 1929. Wildcat drilling in the region has been directed toward two objectives: development of new areas and development of deeper producing sands. Table 1 gives data on 92 of the more important tests.

The more important new field strikes of the season may be listed as follows:

Montana.—Pondera field in Sweetwater County. Following the discovery, in March, 1928, by the Fulton Petroleum Co., of oil in the top of the Madison at a depth of approximately 2000 ft., development of the area was rapid and by the close of the year some 65 wells had been drilled, giving the field a total daily capacity of about 1500 barrels.

Wyoming.—Alkali Butte field in Fremont County. The Texas Production Co. found oil of 39° gravity in the Muddy sand zone at a depth of 4175 ft. There has been considerable trouble in handling the well but it seems to be good for about 400 bbl. per day. The oil contains

TABLE 1.—*Important Wildcat Tests in the Rocky Mountain Area during* 1928

Structure	County	Location			Company	Status, Dec. 31	Results
		Sec.	T.	R.			
					Colorado		
1. Badito—Alamo	Huerfano	4	28 S.	68 W.	Kinney-Coastal—Parker Club	Dlg. at 1350′	Show oil upper part of Pierre
2. Escondido	Huerfano	24	26 S.	68 W.	Kinney Coastal—Texas Co.	Abd. at 2175′	Tested Dakota and Morrison
3. Glade	Dolores	30	41 N.	16 W.	Moody Corpn.	S. D. at 3955′	Bottomed in red beds
4. Greesewood Lakes	Weld	24	6 N.	61 W.	Platte Valley Oil Co.	Dlg. at 4167′	Water in Hygene 3200′. Good show gas above. Show oil below
5. Naturita	Montrose	4	45 N.	16 W.	Indian Petroleum Co.	Abd. at 5185′	Bottomed in dark shale
6. Parallel	Boulder	32	1 N.	70 W.	Repollo Oil Co.	Abd. at 6145′	Water in Dakota
7. Parker Club (Branson)	Las Animas	32	34 S.	56 W.	Parker Club	Abd. at 3873′	10′ in granite
8. Piceance Creek	Rio Blanco	9	2 S.	94 W.	White Eagle Oil & Ref. Co.	Dlg. at 450′	To test Greenriver and Wasatch (Tertiary)
9. Pipe Springs	Bent	27	27 S.	49 W.	Marland Oil Co.	Dlg. at 3987′	In red beds
10. Pole Mountain	Jackson	2	6 N.	81 W.	Prod. & Ref. Corpn.	S. D. for winter at 1900′	
11. Poose Creek	Rio Blanco	10	2 N.	88 W.	Union Oil Co. of Calif.	Abd. at 1017′	Show of oil in Morrison at 495′
12. Rangely	Rio Blanco	24	2 N.	103 W.	Tidewater Assoc. Oil Co.	Abd. at 4770′	
13. Red Rocks	Las Animas	23	29 S.	56 W.	Phillips Petroleum Co.	Abd. at 2575′	Tools in hole in red beds
14. Round Butte	Larimer	7	11 N.	68 W.	Stanley Barrows et al.	Dlg. at 2015′	
15. Table Mesa	Baca	8	30 S.	60 W.	Marland Oil Co.	Abd. at 2085′	Granite, no Pennsylvanian
16. Table Mountain	Jefferson	30	3 S.	69 W.	C. F. Woods et al.	Abd. at 3003′	Dry in Laramie, Fox Hills and Upper Pierre
17. Willard	Logan	36	8 N.	55 W.	Northeastern Colorado Oil Co.	Abd. at 5612′	Small show oil and gas in Lakota
18. Wilson Creek	Rio Blanco	27	3 N.	94 W.	Texas Prod. Co.	Abd. at 5913′	Water in Dakota

				Idaho			
19. Arbon Valley		12	11 S.	33 W.	Gem State Pet. Co.	Dlg. at 3000′	
20. Marsh Valley		19	108	37 E.	Norton Bros.	Casing at 1208′	Show of gas 1208′
21. Meadow Creek		33	3 N.	41 E.	California Co.	Dlg. at 1417′	
22. Payette		33	9 N.	5 W.	Idaho-Oregon Pet. Corp.	S. D. at 1180′	
23. Star Valley		34	7 S.	46 E.	Great West Oil Co.	Dlg. at 2641′ (4–9–28)	
				Montana			
24. Arro Creek	Fergus	27	22 N.	15 E.	Claggett Dev. Co.	Suspended at 2660′	
25. Bears Den	Liberty	31	27 N.	6 E.	Bears Den Oil Co.	Abd. at 3355′	H. F. W. in Ellis
26. Benton Lake	Cascade	34	22 N.	1 E.	Great Northern Mutual	Abd. at 1835′	
27. Brady (Fedland)	Pondera	24	27 N.	1 W.	O'Haire Trustee	Abd. at 1890′	Madison H. F. W. 1814′
28. Cherry Ridge	Blaine	3	34 N.	22 E.	Ohio Oil Co.	Fishing at 2315′	
29. Conrad	Pondera	35	28 N.	3 W.	Trapp Syndicate	Abandoned	
30. Cutbank	Toole	33	35 N.	4 W.	Madeline Oil Co.	Abd. at 2113′	Bottomed in Madison
31. Devon	Toole	22	31 N.	2 E.	Commonwealth Pet. Co.	Abd. at 2370′	Show of oil at 1985′, Madison at 2000′
32. Dry Creek	Carbon	11	7 S.	21 E.	Ohio Oil Co.	Fishing—T. D. 4458′	12 M. wet gas, 2nd Frontier 4458′, small gas Eagle 2350′-2450′
33. Dutton	Teton	2	24 N.	1 W.	Crocker et al.	Abd. 1732′	Ellis-Madison contact dry at 1720′
34. Fowler	Pondera	32	30 N.	2 W.	Ute-Mo Oil Co.	Abd. at 3030′	Tested Madison
35. Kremlin	Hill	34	33 N.	12 E.	Jones et al.	Abd. at 3665′	H. F. sulfur water upper Madison
36. Last Chance	Teton	9	23 N.	2 E.	Craig Speer et al.	Abd. at 1582′	H. F. sulfur water top of Madison 1580′
37. Lincoln	Liberty	7	33 N.	7 E.	Mid-Rocky Dev. Co.	Suspended at 1475′	
38. Little Muddy Cr	Cascade	12	22 N.	2 E.	Allen Oil Co.	Abd. at 3420′	
39. Miller	Carbon	25	9 S.	24 E.	Local Oil Co.	Suspended at 2500′	Sulfur water top of Madison
40. Nye	Stillwater	32	4 S.	16 E.	Empire State Oil Co.	Suspended at 3661′	H. F. W. in Quadrant
41. Oiltana (Brush Creek)	Petroleum	33	16 N.	28 E.	Oakmont Oil Co.	Abd. 1440′	
42. Pendroy	Teton	8	27 N.	5 W.	Continental Dev. Co.	Abd. 2540′	7 bbl. oil after shot at 2530′–34′
43. Pondera	Teton	16	27 N.	4 W.	Fulton Petroleum Co.	T. D. 2076′	3 M. gas in Ellis, 30 bbl. oil in Madison at 2024′
44. Power	Teton	6	23 N.	1 W.	Archer et al.	Abd. 1590′	Water Ellis-Madison contact

Table 1.—(*Continued*)

Structure	County	Location			Company	Status, Dec. 31	Results
		Sec.	T.	R.			
45. Red Dome	Carbon	20	7 S.	24 E.	Atlantic Oil Co.	Abd. 1779′	Probably in Madison
46. Ringling-Cottonwood	Gallatin	35	5 N.	7 E.	California Co.	S. D. 600′	
47. Sweetgrass Hills	Toole & Liberty	10	37 N.	5 E.	Sunburst Oil & Ref. Co.	T. D. 2850′ in Ellis	Good show in basal Kootenal at 2606′–2780′
48. Valentine	Fergus	9	18 N.	26 E.	Montana Major Oil Co.	Suspended at 1200′	
New Mexico							
49. Carrica	McKinley	19	17 N.	7 W.	Continental Oil Co.	Abd. at 3190′	Bottomed in McElmo Dakota water bearing
50. Rattlesnake (Deep Test)	San Juan	2	29 N.	19 W.	Continental—Santa Fe Co.	Dlg. at 6338′	Bottomed in Pennsylvanian
51. Stoney Butte	San Juan	36	22 N.	14 W.	Midwest Ref. Co.	Abd. at 3063′	Show of oil at 770′ & 790′ in Mesaverde
Utah							
52. Ashley Creek	Uinta	23	5 S.	22 E.	Midwest Exploration Co.	T. D. 2720′	I. P. 29 M. gas at 1662′–82′, show oil 1808′
53. Barrier Creek	Wayne	16	27 S.	16 E.	Phillips Petroleum Co.	Dlg. at 4285′	
54. Boulder Knoll	San Juan	17	34 S.	26 E.	Boulder Knoll O. & G. Co.	S. D. at 2640′	
55. Boundry Butte	San Juan	1	43 S.	22 E.	Continental Oil Co.	S. D. for repairs 4525′	
56. Duchesne	Duchesne	13	4 S.	6 W.	Utah Oil Ref.—Midwest Exp. Co.	Abd. at 4760′	Total depth in Tertiary—several small shows oil
57. Elk Ridge	San Juan	30	34 S.	19 E.	Midwest Exploration Co.	Abd. at 4422′	Bottomed in granite
58. Salt Valley	Grand	13	23 S.	20 E.	Utah Southern—Moab Cons. Oil	S. D. 3001′	
59. Sweetwater	Wayne	5	27 S.	14 E.	Texas Production Co.	Abd. at 2885′	Tools in hole
Wyoming							
60. Alkali Butte	Fremont	1	33 N.	95 W.	Texas Production Co.	T. D. 4240 in Morrison	Plugged back to Muddy. 4175′, I. P. 400–600 bbl. 39° oil
61. Alkali Creek	Sweetwater	18	13 N.	99 W.	Prairie O. & G. Co.	Casing at 2480′	
62. Anthills	Niobrara	25	37 N.	63 W.	Continental Oil Co.	T. D. 4105′ Abd.	Oil and water in Muddy at 3900′
63. Baggs	Carbon	35	13 N.	92 W.	Red Feather Oil Co.	Dlg. at 1060′	5 M. gas at 760′–1005′ in Tertiary
64. Bates Park	Natrona	4	30 N.	81 W.	M. C. Weisman	Abd. at 2000′+	Show oil in Sundance, water in Embar and Tensleep

65. Canyon Creek	Sweetwater	2	12 N.	101 W.	Ohio Oil Co.	Dlg. at 1200′	
66. Cottonwood	Sublette	12	32 N.	115 W.	California Co.	Dlg. at 1030′	
67. Cumberland	Lincoln	11	19 N.	116 W.	Quad States Enterprises	Dlg. at 2500′	
68. Ferris (Deep Test)	Carbon	25	26 N.	87 W.	Producers & Refiners Corpn.	T. D. 4523	I. P. 700 bbl. 36° Bé. oil in Tensleep
69. Fiddler Creek	Weston	30	45 N.	65 W.	Teton Oil Co.	Dlg. at 900′	
70. Four Bear	Park	29	41 N.	103 W.	California Exploration Co.	T. D. 3220′	I. P. 40 bbl. black oil in Tensleep
71. Frannie	Park	25	58 N.	98 W.	E. H. Rosenberg et al.	T. D. 2600′	I. P. 250 bbl. 28° Bé. oil in Embar
72. Graybeal	Carbon	16	28 N.	80 W.	Foreman Oil Co.	Suspended at 5165′	Frontier, Dakota and Lakota water bearing
73. Howard	Weston	15	44 N.	64 W.	Allen Oil Co.	S. D. for winter 4300′	Below Frontier—oil and gas showings below 3000′
74. Irvine	Converse	5	31 N.	95 W.	Great Northern Oil Co.	S. D. at 3650′	
75. Little Grays River	Lincoln	36	37 N.	117 W.	Midwest Ref. Co.	Dlg. at 1000′	
76. Little Laramie	Albany	33	17 N.	75 W.	Union Oil Co. of Calif.	Abd. at 2277′	Water in Muddy, Dakota and Lakota
77. Little Sheep Mountain	Bighorn	35	56 N.	95 W.	Prairie O. & G. Co.	Dlg. at 2250′	Show gas in base Madison at 1300′
78. Miller Hill	Carbon	2	17 N.	89 W.	Indian Petroleum Co.	S. D. for winter at 1400′	Bottomed in top of Embar
79. Muddy Creek	Uinta	7	17 N.	116 W.	California Co.	Dlg. at 2131′	
80. Muskrat	Fremont	34	34 N.	92 W.	Prod. & Ref. Corpn.	T. D. 4312′	75 m. gas in Frontier
81. North Sunshine	Park	22	47 N.	101 W.	Union Oil Co. of Calif.	T. D. 3780′	I. P. 30 bbl. 21° Bé. oil
82. Old Woman	Niobrara	4	36 N.	62 W.	Continental Oil Co.	Abd. 2925′	Bottomed in Minnelusa, water
83. Pitchfork	Park	14	48 N.	102 W.	Calif. Exp. Co.—Prod. & Ref. Corpn.	1st well lost 1270′, 2nd Dlg. 225′	
84. Sage Creek (South Franie)	Bighorn	7	57 N.	97 W.	Prod. & Ref. Corpn.	Dlg. at 1355′	
85. Sherrard	Carbon	14	25 N.	89 W.	Prod. & Ref. Corpn.	Dlg. at 2945′	3.5 m. gas at 2372′
86. Shoshone	Park	27	53 N.	101 W.	Ohio Oil Co.	T. D. 4764′	I. P. 300? bbl. from Embar at 4252′
87. Skelton	Hot Springs	23	45 N.	100 W.	Texas Prod. Co.	Dlg. at 525′	
88. Snyder Basin	Sublette	35	30 N.	115 W.	Great American Oil Co.	Dlg. at 750′	
89. Spindletop	Natrona	32	30 N.	82 W.	Geo. Jarvis et al.	T. D. 1032′	I. P. 30 bbl. 22° Bé. oil in Tensleep
90. Steel Creek	Johnson	17	46 N.	82 W.	R. C. Tarrant et al.	Abd. at 3630′	Water in Dakota
91. Tensleep	Washakie	13	46 N.	89 W.	Prod. & Ref. Corpn.	Abd. at 3420′	Tested Tensleep
92. Waterfall	Lincoln	35	22 N.	115 W.	Midwest Ref. Co.	Dlg. at 1912′	

about 60 per cent. gasoline and is one of the best grades of oil ever developed in Wyoming.

In Frannie Field, Park County, E. H. Rosenberg and associates made a rather important discovery of high-grade black oil at a depth of 2600 ft. in the top of the Embar on the Frannie Dome. The oil is 28° gravity with a reported gasoline content of 20 per cent. After tubing was run, the well flowed 1000 bbl. of clean oil in 11 days. Near the close of the year the Rosenberg properties in this area were taken over by the Midwest Refining Co.

At Muskrat dome, Fremont County, the Producers & Refiners Corpn. found 75,000,000 cu. ft. of gas at 1300 lb. rock pressure in the Frontier sands at a depth of 4312 ft. The same well had a considerable showing of oil of 41° gravity in shale at 3820 feet.

At Spindletop dome, Natrona County, George Jarvis and associates now have three small wells producing from the Tensleep. The oil is black oil and comes from a depth of about 1000 feet.

At Ferris field, Carbon County, the Producers & Refiners Corpn. found a 700-bbl. well of 36° gravity oil in the Tensleep below the old production in this area, which comes from the Cretaceous. This can be classed therefore as an important new discovery, as the oil is high grade and from a sand which had not before been known to be productive in this area.

Montana's Oil Industry for 1928

By Ralph Arnold,* Los Angeles, Calif.

(New York Meeting, February, 1929)

The lure of possible new oil fields shut off development of the older Montana fields during the year 1928, cutting down the total production to less than the 1927 mark. However, with the production of oil worth approximately $7,000,000 during the past 12 months, Montana oil producers pushed their total up to $44,000,000 taken from two principal fields during the past 8 years.

The highest prices in the United States for oil of similar gravity gave northern Montana producers a decided advantage and brought up the value of the oil to about the same value as the 1927 production, although the oil runs were 1,000,000 bbl. less.

Production by Fields

The discovery of two new oil fields in the Sweetgrass Arch, in north central Montana, in 1927, diverted attention from the Kevin-Sunburst field. Many operators turned their attention to wildcats and practically all of the drilling contractors were called into the new Pondera and Bannatyne fields. Although discovered in 1927, the Pondera field developed its first commercial production in March of 1928. Mild interest was followed four months later by a rush of operators, and by August practically every string of tools had been moved from the Kevin-Sunburst field to Pondera. The fall months found 40 wells drilling in this field and as the year closed there were 100 producers.

Pondera field is remarkable in that every well thus far drilled within the structure proper has been a producer. Dry holes have been drilled around the field, but none within an area of four sections. Experts estimate that Pondera will produce 5000 bbl. of oil to the acre. The producing area now outlined by wells drilled is expected to produce around 15,000,000 bbl. of oil. Pondera crude brings $1.75. This field has one pipe line and a second line is being laid.

Lack of a pipe line delayed development of the new Bannatyne field, south of Pondera, and also in the Sweetgrass Arch. Bannatyne has 11 producing wells scattered over an area of approximately three sections. Bannatyne is a sand field with a 70-ft. sand in the lower Jurassic, which core-drill tests show to be 60 per cent. saturated. With the completion

* Consulting Geologist.

of a pipe line in the spring the five operators controlling the field expect to start systematic development. This is 1450-ft. drilling, approximately the same as Kevin-Sunburst.

With the egress of operators and drillers to new fields, Kevin-Sunburst had the fewest completions since the discovery year, 1922. Despite the lack of drilling, three new pools were opened up, one an important extension to the southeast, 5 miles from the nearest commercial oil production, in the supposed gas area. The other two were near the top of the vast dome which covers 100,000 acres and is dotted with separate oil pools. The new Steele pool had a 250-bbl. discovery well, while the Morton pool, which came into being on Christmas Eve, had a discovery well with an initial of 1000 bbl. per day.

Cat Creek field, Montana's first commercial oil field, continued its record of consistent production, although showing a steady but gradual decline. This field has had no drilling for three years yet it produced more than 600,000 bbl. of oil during 1928. This field, with approximately 120 acres of producing area, has yielded approximately $18,000,000 worth of oil thus far, with the lower sands untested. A deep test is scheduled in this field during the year 1929. Big companies are said to concede that deep-sand oil is virtually certain, but further prospecting has been delayed while the shallow-sand production continued to hold up.

There was no new development to speak of in either Elk Basin or Big Lake fields.

The production by fields was approximately as shown in Table .

Table 1.—*Approximate Production in* 1928[a]

Field	Barrels	Value
Big Lake	26,518	$ 32,428
Elk Basin	16,948	24,422
Pondera	137,432	240,497
Cat Creek	607,434	1,053,008
Kevin-Sunburst	3,190,607	5,583,563
Total	3,978,939	$6,933,918

[a] Production of last quarter estimated.

Forecast for 1929

The coming year will see Pondera production reach its peak. Favorable weather has allowed winter drilling and 1929 will doubtless see 200 wells in production. A dozen wildcats now drilling in various parts of the Sweetgrass Arch are due for completion during 1929.

The coming year will see the exploitation of two new oil fields discovered during 1928. One is the Dry Creek structure, in southern Montana, where the Ohio Oil Co. has found evidences of a new light oil field. The other is known as Flat Coulee structure, near the Canadian border and the Sweetgrass Hills, where Sunburst Oil & Refining Co. has discovered a pool of high gravity "sweet" oil. Other important tests in the Sweetgrass Hills area, started during 1928, are expected to bring new production to swell Montana's 1929 total.

Operators who have allowed their Kevin-Sunburst production to shrink, in the absence of drilling to offset natural decline, plan a program of approximately 300 wells to bring Kevin-Sunburst production up to the demands of refineries dependent on this crude.

Montana refiners have had a very bad year, with high-priced crude that could not be profitably refined in competition with gasoline from low-priced crudes of the Mid-Continent. Kevin-Sunburst crude is bringing $1.75 per barrel (including 10 c. bonus) while crude of similar gravity in the Mid-Continent has been commanding 40 c. per barrel. There is a movement among refiners to eliminate the bonus, in order to make 1929 more profitable.

The reentrance of several of the Standard group into Montana during 1928 will doubtless be reflected in drilling operations during 1929.

TABLE 2.—*Oil Production in Montana by Years*[a]

Year	Barrels	Value
1921	1,444,620.37	$ 2,337,325.89
1922	2,310,481.76	3,490,482.09
1923	2,553,763.96	3,874,815.65
1924	2,741,180.98	3,624,078.86
1925	4,020,033.84	6,480,561.71
1926	8,070,000.00	10,300,000.00
1927	5,216,248.95	7,041,936.08
1928	3,978,939.00	6,933,918.00

[a] Last quarter of 1928 estimated.

Review of the Appalachian Fields Including Kentucky and Tennessee

By Jerry B. Newby,* Oklahoma City, Okla.

(New York Meeting, February, 1929)

The outstanding features in Pennsylvania and New York during the past year were the buying of acreage for water-flooding in other Pennsylvania fields than the Bradford and Allegany districts, the wide adoption and use of the five-spot plan of development and water-flooding in the Bradford and Allegany districts, the discovery of gas production in the Onondaga lime in southwestern New York and the opening of the T. W. Phillips Gas & Oil Co. Fifth Sand pool in Butler County, Pennsylvania.

Water-flooding has occurred in many other fields than the Bradford, Pa., and Allegany, N. Y., fields. In some the flood was a natural encroachment of edge water, in others the water was introduced into the productive sand through wells either accidentally or intentionally. Most of these floods have not been commercially successful. There has been some interest aroused in the Clarendon field, Warren County, Pennsylvania, by a new and apparently successful flood and other floods have been begun.

Five-spotting in the Bradford and Allegany fields is the plan of water-flood development under which the area to be drilled is laid off in a grid of equal-sized squares with water intakes located at each corner of the squares and oil wells located in the centers of the squares. So far there are two five-spot water floods that are, beyond doubt, commercial successes. There were 600 acres under five-spot flooding at the end of 1928, as against 150 at the end of 1927. By the end of 1929 there will be a total of between 1200 and 1500 acres five-spotted unless a low market for Pennsylvania grade crude oil develops. An increase of 6000 bbl. in average daily production is expected to accompany this development in 1929.

The Belmont-Quadrangle Drilling Corpn. found the Onondaga lime or a higher strata at 3995 ft. north of Bolivar, Cattaraugus County, N. Y., and a number of miles from any other important gas production. When drilled to 4006 ft. the well yielded 3,500,000 cu. ft. of gas and when shut in 1700 lb. rock pressure.

The one oil pool opened in 1928 was in Buffalo township, Butler County, Pa., in October, when the T. W. Phillips Gas & Oil Co. completed a wildcat well in the Fifth sand at 700 bbl. a day, which by the end of

* Vice-president, Petroleum Reclamation Co.

the month was producing scarcely 20 bbl. daily. Paraffin deposition was probably a factor in the rapid decline. Other wells completed near by had an initial production of less than 600 bbl. but are showing much better staying qualities.

The Nineveh pool in Greene County, Pennsylvania, was slightly extended.

All Pennsylvania and New York districts, except the middle district, declined in completions and all except middle and southwestern Pennsylvania, including the Phillips pool, declined in new production. As usual the Bradford and Allegany districts were leaders. Comparative figures follow:

	1927	1928
Completions, all districts	2950	2600
Oil well completions	2650	2400
New production, bbl	6900	5900
New gas wells	190	150

Southeastern Ohio

Aside from the new Clinton sand pool opened in 1927 at Cookston, Harrison Township, Perry County, developments in southeastern Ohio were of only nominal importance. More than 80 producing wells were completed in the pool at Cookston, most of them on the 160 acres in the northwest corner of Sec. 21. The limits of production have been well defined and development is on the wane. The Niagara limestone in Guernsey County yielded a number of wells with an average initial production of 60 bbl.; depth to producing horizon, 3600 to 3700 feet. The Germantown, Keener, Berea, Cow Run and other horizons added their usual quota of small wells all of which were located in proven territory.

Well completions in the southeastern Ohio district decreased for the second successive year, reflecting the low market for eastern crudes. More than 75 per cent. of the new production has been coming from the Clinton sand. Figures for the past three years follow:

	1926	1927	1928
Completions	1,100	900	750
New production, bbl	14,000	12,000	18,000

West Virginia

Low market prices for Pennsylvania crude oil curtailed wildcatting, concentrated development work on proven territory and directed attention to methods for rejuvenation, reshooting, cleaning-out and deepening. Completions and new production for the past two years were as follows:

	1927	1928
Gas well completions*	410	390
Oil well completions *	275	200
New production, bbl	3600	2600

* Percentage of dry holes unchanged.

Late in May a well on the Midcap farm, Wetzel County, started off at 840 bbl., but within a month was down to 51 bbl. A number of dry holes and a 75-bbl. well were completed in the vicinity of the Midcap well. Some 10 wells in Roane County started off at from 40 to 50 bbl. per day from the Big Injun and Berea sands. Most of the new wells were inside locations or small extensions of old fields and averaged 13 bbl. initial production. Increases in production of from 100 to 400 per cent. were reported for gas or air pressure and reshooting and cleaning out.

Kentucky and Tennessee

In Kentucky 60 per cent. of the well completions and 90 per cent. of the new production were in the Tri-County field of Ohio, Daviess and Hancock counties. Ohio County led the district with more than a third of the total well completions for the state and 57 per cent. of the new production, showing little change compared with 1927. Well completions in Daviess County increased from 50 to 359 and new production from 1000 to 12,000 bbl. Development centered around the Pellville and Ambrose or Weller pools.

The general region of the Tri-County field is expected to become one of the most profitable areas in Kentucky. The wells are completed at 400 to 800 ft. and development costs are correspondingly low. The productive horizons are true silica sands, very fine grained and moderately soft. They should have a long productive life. Initial production averaged 42 bbl. per well for all producers, gas wells and dry holes completed in Ohio County and 35 bbl. for Daviess County. Dry holes made up 28 per cent. of all completions in Ohio County and 33 per cent. in Daviess County.

There was some wildcatting in counties adjoining the Tri-County field but very little production of oil or gas. Another scene of activity was the Lecto extension of the Glasgow pool in Barren County. Only casual work was underway in the rest of the state. Comparative figures follow:

	1927	1928*
Well completions	1,150	1,400
New oil wells	780	970
New production, bbl	31,000	38,000

Tennessee showed no marked change from the preceding year. Runs from the entire state were less than 150 bbl. per day.

* The increases came from development in Daviess County. There was no change in gas wells.

Central and Northwestern Ohio in 1928

By Jerry B. Newby,* Oklahoma, City, Okla.

(New York Meeting, February, 1929)

In the central Ohio area well completions and new production each increased 60 per cent. in 1928 over the previous year. Gas wells increased only 27 per cent. The ratio of dry holes to total completions was unchanged. Ashland County led with 113 completions; a new pool in the shallow Berea sand near Jeromesville stimulated activity. Licking County in the Clinton deep sand territory, however, lead in new production with 972 bbl. Two other deep sand counties followed closely, Coshocton with 831 bbl., and Muskingum with 718 barrels.

The Trenton rock or Lima field of northwestern Ohio declined sharply in oil well completions to 130 for 1928 from 210 for the previous year. New production increased from 3000 to 6100 bbl., the increase coming from the Murphy pool in Liberty township, Seneca County. The total of gas wells was unchanged as compared with 1927. The ratio of dry holes to total completions rose from 13 per cent. in 1927 to 27 per cent. in 1928.

The largest producer in the Murphy pool made 1200 bbl. in the first 24 hr. The total depth of the wells in this pool averages 1475 ft.; average initial production, 125 barrels.

* Vice-president, Petroleum Reclamation Co.

Petroleum Development in Illinois and Indiana during 1928

By Gail F. Moulton,* Urbana, Ill.

(New York Meeting, February, 1929)

The production of petroleum in Illinois in 1928 was approximately 6,500,000 bbl., a decline of about 500,000 bbl. from the previous year and of about 1,500,000 bbl. from 1924. Production increased about 200,000 bbl. in Indiana to slightly less than 1,000,000 bbl. Production for 1929 is estimated at approximately 6,000,000 bbl. for Illinois and 1,000,000 bbl. for Indiana.

Illinois

Because production from most of the wells in the state has declined to a small daily average and the low prices for crude oil discouraged wildcatting, the number of wells drilled fell below that for any previous year since the development of commercially important production in the state. The Ohio Oil Co. discovered a pool of apparent commercial importance in southwestern Illinois near Dupo, in St. Clair County, and favorable showings of oil were encountered in a well in southeastern Illinois, near Harrisburg in Saline County. New production from the Dupo area is expected to check the rate of decline for the state.

The following table[1] summarizes field developments for 1927 and 1928 (for important detail by counties see notes at foot of table):

	1927	1928
Completions	162	145[a]
Initial production, bbl	2244	1840[b]
Dry holes	66	58[c]
Gas well completions	13	8[d]
Old wells abandoned		45[e]

[a] Crawford, 44; Lawrence, 28; Wabash, 40.
[b] Crawford, 501; Lawrence, 403; St. Clair, 165 (4 completions); Wabash, 668.
[c] Crawford, 12; Wabash, 19.
[d] Crawford, 6.
[e] Lawrence, 21; Wabash, 15.

The discovery well in the Dupo field in St. Clair County, produced about 150 bbl. per day from the Trenton lime at 660 ft. It is located in a northern extension of the Columbia-Waterloo anticline on which the Waterloo pool was developed in 1921. The best information on the

* Petroleum Geologist, Illinois State Geological Survey. Introduced by M. M. Leighton.

[1] *Oil and Gas Journal* reports supplemented by reports of Illinois Geological Survey scout.

well near Harrisburg in Saline County, indicates that it will probably produce 5 bbl. or less per day.

The principal developments in Wabash County were in the vicinity of Allendale. One deep well to the Ste. Genevieve lime was drilled south of Allendale but there was little other development except in drilling to the Biehl sand in new wells near older producing wells.

Early in 1928 three wells were drilled in the southeast part of Lawrence County, about a mile south of the old Murphy pool, but production was not sufficient to warrant a more extensive development. Drilling in the northern part of Petty township along the Crawford County line resulted in a northern extension of the producing area of Lawrence County. Production was from Lower Chester sands corresponding to the Kirkwood, Tracey and possibly the McClosky sands of the Lawrence County fields. A portion of this development also took place in Southwest and Martin townships, Crawford County, and is still in progress.

The most interesting well drilled in Clark County was a test by the Trenton Rock Oil & Gas Co. on the Martinsville dome. It was drilled through the producing pays in the Kinderhook shale and the top of the Devonian limestone to test the Kimmswick (Trenton) limestone. Reports are that it will not make a very profitable producer.

A well drilled on the Media structure in Henderson County by Pendarvis et al., in the location recommended in a report by the State Geological Survey, found a fairly good showing of oil at the horizon of the Hoing sand, the producing bed in the Colmar-Plymouth field about 30 miles to the south. A well was completed south of Macomb in McDonough County in the Gin Ridge district, 4 miles east of the producing area at Plymouth. Other interesting wildcat wells, all down more than 2000 ft., were drilled in Clay County about 25 miles south of Effingham, in Marion County, about 10 miles south of Salem, near Kell, and in Jefferson County about 7 miles south of Mt. Vernon near Ina. The Clay County well is still operating; the other wells have been abandoned.

Indiana

For the second successive year total production showed a slight increase. This was again due to the considerable increase in the production in southwestern Indiana, which more than offset the decline of the older Trenton rock fields in the northeastern section of the state.

The Shell Company's well in Gibson County, about 3 miles west of Oakland City, obtained oil and gas production from a sand near the base of the Chester at 1400 ft., and it appears that a new producing area has been discovered. The new well is about 5 miles south of the Oatsville pool discovered in 1921. A second discovery was made in Spencer County, north of the Owensboro, Kentucky, field. No wells of important size are reported for this area but operators are likely to continue drilling.

Several wells were drilled in Pulaski County near Francesville in an attempt to get new production from the Trenton lime in the vicinity of some wells drilled in 1888.

Drilling operations in 1927 and 1928 are summarized in the following table[2] (for detail by counties see notes):

	1927	1928
Completions	246	206[a]
New production, bbl	3776	2420[b]
Dry wells	107	82[c]
Gas wells	37	38[d]
Old wells abandoned		94[e]

[a] Gibson, 42; Harrison, 12; Pike, 21; Spencer, 16; Sullivan, 28; Vigo, 27.

[b] Adams, 56 bbl.; Gibson, 550; Pike, 180; Spencer, 93; Sullivan, 503; Vigo, 975.

[c] Gibson, 19; Pike, 10.

[d] Harrison, 10.

[e] Delaware, 29; Huntington, 18; Jay, 14; Pike, 10.

Along the Vigo-Sullivan county line in the vicinity of Middletown, a large number of wells were completed in the pay near the top of the Devonian lime at about 2100 ft. There was also new drilling in the vicinity of the Mt. Olympus pool in northern Gibson county, in the Francisco area in central eastern Gibson county, and in the southwestern part of Daviess County. Deep wildcats were drilled a few miles north of Evansville, and a few miles south of Covington without success.

Although the Middletown and Francisco pools, which have made important contributions to the new production of the state during the past two years are largely drilled up, some additional drilling is looked for in both of these areas during 1929. It is expected that this development combined with the new developments already started in Spencer and Gibson counties will probably offset the decline in production of the older wells in the state.

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[2] Statistics compiled from *Oil and Gas Journal.*

Chapter IV. Petroleum Production—Foreign

World Petroleum Production in 1928

By Valentin R. Garfias,* New York, N. Y.

(New York Meeting, February, 1929)

The world's petroleum production in 1928 is estimated at 1,322,896,000 bbl., an increase of about 62,000,000 bbl. over 1927, as compared with an increase of over 133,000,000 bbl. in the previous year. The daily average was close to 3,600,000 bbl., of which the fields on the American continent produced about 84 per cent.

The most important development during the year has been the partial success of the attempts to temporarily control production without appealing to legislation and, as a consequence, the increasing realization that, in order to reach a permanent cure for this situation, some form of legislation is necessary to make possible the conservation of the oil supply and the stabilization of the industry. The importance of such a control over American production is not merely local but worldwide, as the American oil supply is now and for years to come will be the controlling factor of the industry.

United States.—Production in the United States, which in 1927 increased about 15 per cent. over the previous year, remained practically stationary in 1928, the total being estimated at 902,000,000 bbl., or 68.2 per cent. of the world's output. This uniformity in production during the last two years was due primarily to the curtailment of output from wells already drilled, it being estimated that the available or shut-in production at the end of the year was close to 500,000 bbl. per day, or equivalent to the combined production of Venezuela and Russia, the countries ranking second and third.

Venezuela.—With a production estimated at 106,000,000 bbl., Venezuela has trebled its output in the last three years. The increase in 1928 was 43,000,000 which placed this country as second in rank, a position which it should easily maintain for years to come. The output could have been considerably larger had not the oversupply in the United States made it advisable for Venezuelan operators to enter into tentative conservation agreements.

Russia.—In Russia, production has doubled in the last five years, and reached a new peak in 1928 with an output estimated at 87,800,000 bbl., or an increase of 10,000,000 bbl. over the previous year. Difficul-

* Manager, Foreign Oil Department, Henry L. Doherty & Co.

ties arose during 1928 between American and English companies in reference to the marketing of Russian products, but such disagreements are now on the road to amicable settlement.

Mexico.—The Mexican production has steadily declined since 1921, the 1928 output being estimated at 50,150,000 bbl., or about one-half that of 1926, a condition which has been brought about by the gradual decline of production and the lack of new development. This downward trend should not materially change in the near future and it is therefore expected that Persia will outrank Mexico during 1928 as the fourth producer.

Persia.—The fields of Persia continue their gradual methodical expansion, offering a convincing proof of the remarkable benefits derived by unit operation. The company controlling these fields has been able to regulate production in line with market requirements and to conserve the reserves underground, anticipating future needs and higher prices.

Dutch East Indies.—The fields of Dutch East Indies have steadily produced during the last five years around 24,000,000 bbl. yearly, the production in 1928 being estimated at 28,500,000 bbl., a new high record for these fields.

Colombia.—The production of Colombia has trebled in the last three years, reaching 19,900,000 bbl. in 1928. The entire output comes from Las Infantas field in the Magdalena Valley, it being estimated that if additional pipe-line facilities are provided the fields of Colombia will outrank those of Dutch East Indies in 1929.

Peru, Argentina, Trinidad and Ecuador.—The fields in these countries reached new peaks during 1928, Peru doubling its production in the last six years, Argentina and Trinidad in the last five and Ecuador during 1928.

Position of United States

Conditions in 1928 again clearly show that the stability of the world's petroleum industry hinges primarily on the intelligent and effective conservation of American petroleum resources. This can best be realized when it is considered that the individual production of California, Texas and Oklahoma is now equivalent to the combined yield of Venezuela, Russia, Mexico and Persia, and that the output of individual companies in the United States exceeds, in fact almost doubles, the total production of Persia. The United States, therefore, is now and should remain for years to come the dominating factor in the industry, and for this reason it is urgent that the American producer establish without further delay effective machinery that will eliminate needless overproduction with its accompanying inevitable waste. Many suggestions have been made as to the remedy for present conditions, such as voluntary restriction, proration, cooperative agreements backed by state commissions, moratorium in drilling, levying a tax on oil in storage, but all these circumvent

rather than attack the real issue—the present divided ownership of pools and the laws regulating such ownership, which make it impossible to develop the pool as a unit.

The American petroleum industry is coming to realize more and more clearly that the solution, in fact probably the only effective remedy, will have to come through federal legislation that will remove the basic trouble in the ownership of pools so as to allow their operation on the unit plan. Such a program was outlined by Henry L. Doherty over 4 years ago and was presented by him to the Institute at the February meeting in 1925.[1] While this plan was not received with favor by the industry at the time, there has been a growing appreciation that the difficulties of the conservation of the oil resources and of the stabilization of the industry are rooted in the divided leasehold and the control of the situation by the royalty owner, and that these difficulties cannot be removed except by legislation along the lines suggested by Mr. Doherty.

World Petroleum Production*
In Thousands of Barrels

	1928	1927	1926
United States	902,000	901,129	770,874
Venezuela	106,000	63,134	37,226
Russia	87,800	77,018	64,311
Mexico	50,150	64,121	90,421
Persia	42,080	39,688	35,842
Rumania	30,600	26,368	23,314
Dutch East Indies	28,500	25,967	21,242
Colombia	19,900	15,002	6,444
Peru	11,970	10,135	10,762
Argentina	9,100	8,630	7,952
India	8,300	7,878	8,728
Trinidad	7,750	5,712	5,278
Poland	5,530	5,342	5,844
Sarawak	5,290	4,943	4,942
Egypt	1,840	1,267	1,188
Japan	1,800	1,700	1,900
Ecuador	1,090	537	214
Germany	683	663	653
Iraq	650	200	
Canada	618	477	364
France	520	504	478
Sakhalin	509	440	181
Czechoslovakia	150	149	150
Italy	43	44	48
Others	23	25	33
	1,322,896	1,261,073	1,098,389

* Figures furnished by the United States Bureau of Mines.

[1] H. L. Doherty: Suggestion for Conservation of Petroleum by Control of Production. Production of Petroleum in 1924, A. I. M. E.

Petroleum Development in Venezuela during 1928

By E. B. Hopkins* and H. J. Wasson,* New York, N. Y.

(New York Meeting, February, 1929)

Throughout 1928, production of oil from Venezuela steadily increased, and at the close of the year, the output was at the rate of nearly 400,000 bbl. a day. The total for the year was approximately 106,500,000 bbl., representing an increase of about 66 per cent. over the 63,000,000 bbl. produced in 1927.

Venezuela now stands next to the United States as the second largest oil-producing country in the world; and there is abundant evidence to suggest that this relationship will endure for a number of years.

Reserves were notably increased in the Lake shore fields, and the potential output of the Maracaibo Basin is much greater than the current production. In spite of this, the percentage of production increase was comparatively moderate, and the rate of this increase continued to fall off slightly, as has been the case for the last three years. This does not suggest that further annual increases in Venezuelan output will not materialize; only that the rate of these increases appears to be on the decline, and that with every succeeding year the future tendency will be in the direction of a stabilized level of output. The following table shows the production trend of the country since 1925:

1925 increase over 1924,	132 per cent.
1926 increase over 1925,	80 per cent.
1927 increase over 1926,	75 per cent.
1928 increase over 1927,	66 per cent.

Many factors will work to prevent a reversal of this trend, but the principal ones are strong ownership in large-acreage units, and the probable indisposition of the world market to absorb a more rapidly increasing Venezuelan output at prices profitable to the producers. The distress oil element is not a factor in Venezuela; also, any unforeseen jump, such as results in the United States from the discovery of a Seminole or a deep sand at Long Beach, or Santa Fe Springs, is impossible in Venezuela, on account of lack of means for transporting a sudden surplus of oil, and the slowness with which additional transportation equipment in the form of shallow-draft tankers can be obtained.

* Petroleum Geologist.

There will be a steady increase for the next few years but the advance will in all probability be orderly and will of itself cause little disturbance to the world price structure. Eventually, and possibly within a few years, the apprehension concerning the Venezuelan oil reserves as a market menace may give way to a feeling of gratitude that such reserves are within convenient reach of the western hemisphere. The present psychology, and general outlook of the industry, is steadily changing toward a more enlightened economic level, and with this change will come a more general recognition of the fact, already axiomatic in certain other extractive industries, notably copper, that a reserve is only a menace when it invites to excess exploitation. In Venezuela production has come to its present magnitude rapidly, to be sure, but the large rate of production is not inconsistent with the enormous expansion of visible reserves that has taken place coincidently, nor with the initial capital expenditures that were necessary before any of this oil could be made available for world consumption.

Field Developments

Despite the facts of the case, there prevails in many quarters an impression that the Venezuelan operators during the past year have been

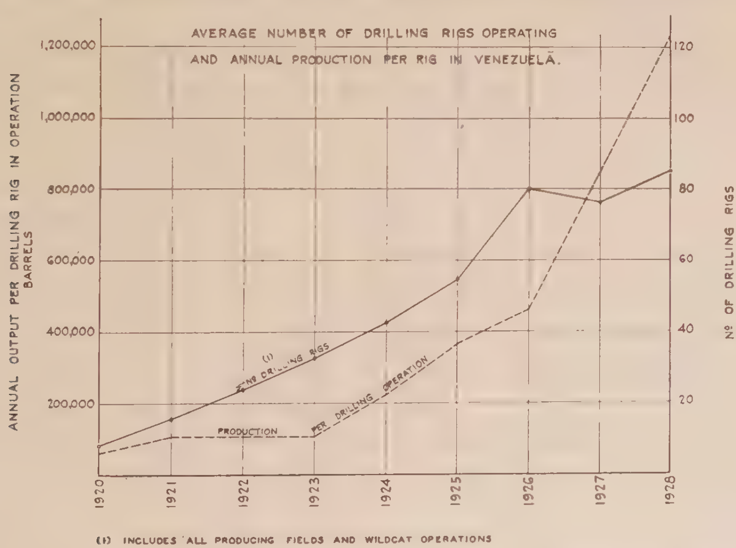

Fig. 1.—Average number of drilling rigs operating in Venezuela and annual production per rig.

conducting a greatly accelerated production campaign. What has actually happened is that at the close of the year two fields were shut down completely, and total drilling activity for the entire country was only slightly above its 1927 level. A comparative idea of the rate of activity over the past few years is given in Fig. 1, which also shows how

increased production has come about principally as a result of finding more prolific territory than as a result of intensive drilling.

One new field, Hombre Pintado, has been added to the list of producers, though the output during 1928 was very limited. The Hombre Pintado field, the real importance of which remains to be determined, was discovered by the Standard of New Jersey (now Creole), late in 1927. Several wells were completed last year, and a pipe line connection was made with the El Mene field of the British Controlled Oilfields, where access to Lake Maracaibo is to be had through the B. C. O. line.

Hombre Pintado field is in the State of Falcon, about 10 miles east of the El Mene field, and appears to be another similar high-gravity oil field. The pay levels are encountered at depths ranging from 490 to 1657 ft., and the initial production of the wells ranges from 100 to 400 bbl. In November, the three wells in the field that were definitely on production produced 1693 bbl., or an average of about 20 bbl. per well per day.

Another potential area now approaching a producing status is the Totumo field, of the Creole Corpn. Totumo, also called Rio Palmar field, is in northern Perija, near the Palmar River. The original discovery well was drilled back in 1914, but legal difficulties over title to the concession held up further development for years. With the legal situation straightened out, the Creole is going ahead rapidly, and at the close of the year had repaired the old discovery well, completed one new producer, and had four rigs running.

The depth of production is around 3000 ft., and the wells completed have shown initial productions of up to 2500 bbl. No pipe-line outlet for this field has been constructed as yet, and some further drilling will doubtless be required to definitely prove up a field that will warrant this expense.

The Tarra field, in the District of Colon, is rapidly approaching a shipping status. A 90-mile pipe line, leading from the field to the lake, is now under construction, and should be transporting oil by the middle of 1930. From wells already drilled, this field at present has a potential production of about 15,000 bbl. a day. Six strings of tools are busy drilling up more territory, and by the time the 20,000-bbl. capacity pipe line is completed, the field will be able to supply oil to the capacity of the line.

A fourth area, apparently on the verge of commercial production, is known as the El Mene del Salto (or simply El Mene) field, in eastern Falcon. This property has been under development by the North Venezuelan Petroleum Co. for several years. Three wells, thought to be of commercial importance, have been completed, with productions ranging from 100 to 400 bbl. per day. The oil has a gravity of 36° to 40° Bé., and the productive levels have been found from 700 to 2000 feet.

The four areas just mentioned, Hombre Pintado, Totumo, Tarra, and El Mene del Salto, are at present the most likely known sources from which new production may be expected to come. All of them together will have little effect, however, on the 1929 figures; and in 1930 will scarcely add more than 30,000 bbl. per day to the Venezuelan total.

In addition to these four areas, which may be considered as near future potential fields, there were completed in 1928 two wildcat wells, which obtained oil in considerable quantity and appear to justify their being recorded as discovery wells. Both of these are in the District of Mara; the one being known as Amana No. 1, of the Venezuelan Gulf Oil Co., and the other Netick No. 1, of the Orinoco Oil Co. (Pure Oil subsidiary). In Amana several oil levels were encountered between 3300 and 4200 ft. The reported results of production tests indicate a rating of about 300 bbl. initial production for this well, the oil being 28° gravity. No further work is being done in the immediate vicinity of Amana, but the area is one that must be considered as at least semiproved.

The other likely looking wildcat test in Mara, Netick No. 1, was drilled by the Pure Oil Co. It struck a sand that tested 200 bbl. (flowing by heads) of 31° gravity oil. The well made about 350,000 cu. ft. of gas daily, with the oil, and recorded a closed-in pressure of about 700 lb. The depth of the Netick oil level is around 5300 ft., and though at this depth there is considerable question concerning the value of a 200-bbl. well, the showing may be considered as encouraging for commercial levels at greater depth, or more prolific sands, elsewhere in the same general area.

None of these operations in Mara will lead to immediate additions to the country's production. In each case the wells mentioned, and the other wildcats now drilling near them, are at a considerable distance inland from the lake, and pipe lines will not be justified until a substantial reserve is more or less definitely proved. No oil from Mara is likely to come on the market during 1929, and probably not until 1931 will this district figure prominently in Venezuela's output.

Of more immediate importance to the production picture even than the four mentioned potential fields is the wildcat program now getting under way in the District of Urdaneta. Two wells are at present drilling, and at least six more wildcat locations in this area are definitely scheduled for the near future. Some of these wells, including the two already started, will be on or very close to the shore. A prolific discovery in any of these close-to-shore wells can be quickly developed into a commercial field, as the land transportation problem at least is practically eliminated.

One other possible source of production during 1929 is the so-called Urumaco, or El Mamon field, in Falcon. The presence of oil was first established here by a well drilled in 1927. This well, El Mamon No. 1,

drilled jointly by the Standard Oil of California and the Beacon Sun Co., had to be abandoned because of mechanical trouble. No. 1-A was drilled during 1928, but also for mechanical reasons failed to make a producer.

The showing encountered in these wells, however, afforded practically conclusive proof that a commercial field could be opened up, and during 1929 further drilling will be done to determine the importance of this area. The locality is comparatively close to the shore of the Caribbean Sea, and any oil produced can be readily brought to tidewater without great expense for pipe-line construction. Here again, though, the chances are that production from this section will not appear until next year.

Wildcat Drilling

Some five wildcats completed during the year may be classed, at least provisionally, as moderately successful operations. Gulf-Amana No. 1, and Orinoco Oil Co. Netick No. 1, in the District of Mara, have already been mentioned. The full list of these potential producers is given in Table 1.

Table 1.—*Important Discovery Wells Drilled in Venezuela during* 1928

Well	Company	Location	Est. I. P., Barrel
Moneb 2	Creole Petr. Co.	Monagas (E. Ven.)	300
Las Palmas 1	Creole Petr. Co.	Falcon	100
Amana 1	Gulf Co.	Mara	300
Netick 1	Orinoco Oil Co.	Mara	100
Mauroa 2	B. C. O.	Falcon	Gas well

None of these is on active production at the present time except Mauroa No. 2, which is furnishing part of the gas used in the gas-lift system at El Mene.

Besides these wells, 19 failures were recorded during the year. Several deep tests south of the Lagunillas and Mene Grande fields were carried down to depths of 5000 ft. or more without finding commercial production; and as a result it would appear that the oil prospects over a large area in the southeastern part of the basin will be confined to very deep sands. The other wildcat failures were scattered over a wide area, including two in the District of Mara, one in Miranda, three in Trujillo (southern end of the lake), one in eastern Venezuela, and seven in the State of Falcon.

With respect to developments in the producing fields, the situation changed but little during 1928. All of the production, with the exception of a few barrels from the new Hombre Pintado field, came from the old fields; and the increase in production was accompanied by only a very slight increase in drilling activity.

The principal results of the year's accomplishment are summarized in Table 2, and the following review of the developments in the fields.

TABLE 2.—*Venezuelan Oil Statistics to Dec.* 31, 1928

FIELD	DRILLING SUMMARY								PRODUCTION			AGE OF FIELD YEARS	GRAVITY OF OIL DEGREES BEAUMÉ
	WELLS DRILLED PRIOR TO 1928		WELLS DRILLED YEAR 1928		TOTAL WELLS TO DEC 31, 1928		AVE DEPTH OF HOLE DRILLED IN 1928	WELLS DRILLING DEC. 31 1928	PRIOR TO 1928	DURING YEAR 1928	CUMULATIVE TO DEC. 31, 1928		
	PRO-DUCERS	DRY HOLES	PRO-DUCERS	DRY HOLES	PRO-DUCERS	DRY HOLES							
MENE GRANDE	13	(1) 3	2	(1) 2	49	(1) 5	2888	2	37,504,882	13,879,142	51,384,024	12	18
LA ROSA	318	0	117	1	435	1	2436	15	53,566,861	25,271,038	78,837,899	6	25
EL MENE B C O LTD.	131	54	25	21	156	75	1100	7	8,437,109	1,913,104	10,350,213	5	36
LA PAZ	26	3	0	0	26	3		0	1,306,427	6,962	1,313,389	4	25
CONCEPCION	64	1	0	0	64	1		0	1,637,759	195	1,637,954	4	36
AMBROSIO	42	3	4	1	46	4	2709	0	1,989,717	1,843,214	3,832,931	3	24
PUNTA BENITEZ	29	2	9	2	38	4	2628	0	892,884	1,301,967	2,194,851	3	26
LAGUNILLAS	71	0	190	1	261	1	3490	30	30,307,913	61,596,713	91,904,626	3	17.5
LA TARRA	15	8	5	2	20	10	<263	4	175,000	143,250	218,250		30
RIO DE ORO	4	0	0	0	4	0		0	50,000	0	50,000		27
GUANOCO	6	0	0	2	6	2		2	858,906	383,457	1,242,363	3	10
HOMBRE PINTADO	0	0	4	0	4	0	2003	2	0	30,942	30,942	1	
TOTUMO	1	0	1	0	2	0	2500	4	0	47,570	47,570	1	
EL MENE, TUCUYO OF. LTD	2	3	1	3	3	6	1898	2				2	
WILDCAT OPERATIONS	9	100	5	19	14	119		13					
TOTAL	653	181	373	54	1228	241		81	138,727,458	108,417,554	243,045,002		

(1) INCLUDES HOLES ABANDONED BECAUSE OF MECHANICAL DIFFICULTIES AND OTHERS THAT HAD SHOWINGS OF OIL OF VARYING DEGREES OF IMPORTANCE

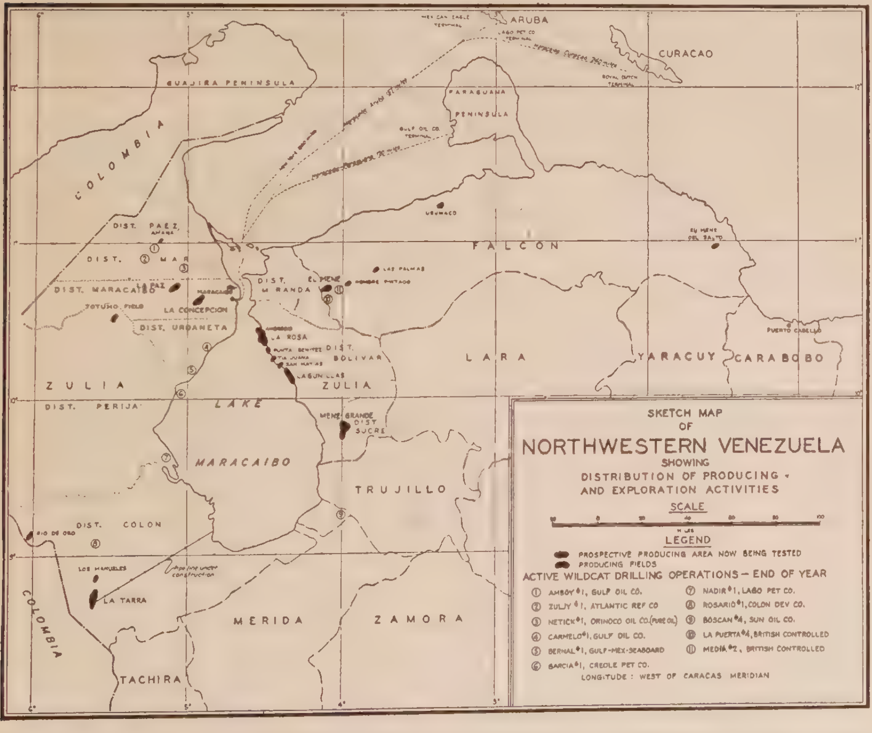

FIG. 2.—MAP OF NORTHWESTERN VENEZUELA SHOWING DISTRIBUTION OF PRODUCING AND EXPLORATION ACTIVITIES.

The accompanying sketch map of northwestern Venezuela (Fig. 2), shows the location of the various localities, and wells mentioned throughout the article.

Lagunillas Field

Throughout the year, the center of production activity was in the Lagunillas area, the southernmost of the lake-shore fields. Some 190 producing wells were completed during the year without a single dry hole having been recorded. Production is obtained at depths ranging from 3200 to 4200 ft., the deepest wells being to the south. Initial productions average around 3000 bbl., with shut-in casing pressures of 200 to 1000 pounds.

The field is now about 7 miles long and 2½ miles wide, though these figures both for length and width will in all probability be considerably increased. Drilling has extended out into the lake for over a mile from shore, some of these outlying wells being in water 25 ft. deep. The economical construction of these deep-water derrick foundations presents an interesting engineering problem that is receiving much attention.

During 1928 Lagunillas produced at the average rate of 169,000 bbl. per day from 261 wells. It has been further established that the oil zone is very prolific, and several wells have passed the 1,000,000-bbl. individual output mark; with two or three having better than 2,000,000 bbl. to their credit.

Practically all the Lagunillas wells are flowing, and it is as yet impossible to foretell the probable rate of decline for any large part of the field. In the light of the results to date, it appears that a very substantial percentage of the proved acreage will yield better than 65,000 bbl. to the acre.

La Rosa Field

La Rosa field, including Ambrosio and Punta Benitez, now covers an area of some 13,000 acres, which can be considered proved territory. It is separated from Lagunillas to the south by a 12-mile stretch, from which no production is at present being obtained. However, even in this gap, there are two potential localities: Tia Juana, and San Matias, where a small amount of drilling has demonstrated the probable existence and continuity of commercial production, between the two fields.

The notable occurrence of the year at La Rosa was the extension of proved territory into the lake for some 2 miles from shore, and the final closing of the gap between the Ambrosio area to the north, and La Rosa proper.

The Ambrosio section, in which some 50 wells have been drilled, was shut in for the greater part of the year, but commenced shipping in quantity in November. Production from the older parts of La Rosa field is now largely obtained by pumping, or gas-lift. In these sections substantial well-output declines have taken place, and some idea of the ultimate yield per acre can be ascertained. It appears that on the aver-

age La Rosa field will yield considerably less, acre for acre, than Lagunillas. The question is somewhat obscured because of the passing up of some of the producing levels in some wells, and failure to deepen certain other wells to known productive horizons. However, a fair estimate would seem to be an ultimate yield of 40,000 to 60,000 bbl. to the acre for a large part of the field.

Mene Grande Field

Only 14 completions were recorded at Mene Grande during 1928, and for several months new drilling was completely at a standstill.

This is a "one company field," and enjoys complete freedom from the problems arising in areas where competitive drilling prevails. In spite of the cessation of drilling, production was well maintained, and the year's record presents the spectacle of a field in which only 14 wells were drilled, producing about 14,000,000 bbl. of oil.

During the year, the productive potentialities of the deeper horizons were further revealed. Only a few wells have been deepened into the so-called "Pauji zone" but the results so far obtained indicate exceptional possibilities. One of the wells deepened to the lower sands in February produced over 700,000 bbl. to the end of the year, and appears to be capable of passing the 1,000,000-bbl. mark by a wide margin. This well was originally completed in the upper sands in 1924; it is situated in the older part of the field. It is evident that potentialities of this lower zone necessitate an upward revision of the estimated per acre yield for this field. An old figure of 25,000 bbl. to the acre ultimate yield was commonly assigned to Mene Grande, but this estimate now appears to be considerably too low.

The area of proved territory covered by the Mene Grande field, which is now in its twelfth year of productive life, is approximately 4000 acres; 154 wells have been completed to the end of 1928, and the limits of proved territory are still only partly defined.

El Mene Field

This field, like Mene Grande, is a unit operation, under sole control of one company. It is the oldest and largest of the two "sweet oil" fields, in Venezuela, the other being La Concepcion. Production comes from a shallow average depth of about 1100 ft. The limits of the pool were not extended during the year, and the full extent of productive territory, which is now pretty well in sight, covers an area of about 900 acres. Despite the lack of new flush territory to draw from, production during 1928 was well maintained, due in large part to the installation of a modern gas-lift system throughout the field.

Guanoco Lake Field

Far from the Maracaibo Basin, in the extreme northeastern tip of Venezuela, the New York & Bermudez Co. (General Asphalt subsidiary), continued small-scale drilling and production activities.

At the close of the year, production was running about 1000 bbl. per day, and two strings of tools were in operation.

The oil from this field is of about 10° Bé. gravity, and is used in connection with the asphalt business of the company.

Other Fields

La Paz and La Concepcion, the two fields on the west side of the lake, were shut down during the year. Active drilling was carried on in the Tarra field throughout the year, but as previously noted, production from this locality must await the construction of the projected pipe line.

Production Outlook

Custom and precedent, as well as a widespread general interest in the subject, impose an obligation on whosoever essays the role of oil reviewer to attempt also the role of prognosticator. For several years now this service, if it may be so described, with respect to Venezuela, has been annually performed and duly presented at the February meeting of the Institute. Heretofore a gratifyingly high degree of accuracy has attended the several efforts in this direction undertaken by the authors. However, in this year's attempt to provide similar data, an unusually large number of uncertainties must be taken into account, and accordingly our 1929 estimate of Venezuelan production is offered with some misgivings and a plea that its necessarily tentative character be clearly recognized.

Summing up all the factors that may influence the 1929 production record, it is quite apparent that the contribution from flush new fields will be small. It is not only possible, but probable, that the new fields, and new wildcat operations will result in substantial additions to reserve, but not much oil from these expected new sources is likely to come on the market in 1929. The one occurrence that might disturb this prediction would be the discovery of prolific production in one of the wildcats now drilling along the west shore of the lake. Even in this case, the actual exports of oil will not be immediately effected, as before oil can be moved out of the Lake of Maracaibo, especially constructed shallow-draft tankers must be available, and the existing combined tanker fleet of all companies is employed at capacity with oil already in sight from the old fields, and will continue to be so employed throughout the year.

The point to note with respect to Venezuela's annual exports is that the figure is controlled entirely by the capacity of the shallow-draft

tanker fleets, which transport the oil from inside Lake Maracaibo to the ocean terminals situated on deep water.

New discoveries in the field, and new fields coming into production, are of secondary importance, in a broad consideration of Venezuelan oil, from the standpoint of its effect on the United States price structure. The most important controlling factor is shallow-draft tanker capacity.

At the close of 1928, there were in service some 70 vessels, especially designed for the transport of oil over the bars at the entrance to the Lake of Maracaibo. This fleet was divided between Royal Dutch, Lago Petroleum Corpn., Gulf Co., Mexican Eagle, and Creole Petroleum Corpn. During the month of December, it moved approximately 10,000,000 bbl. (330,000 bbl. per day), which represents practically the maximum capacity of the fleet as of the end of the year. During the present year certain additions will be made to this fleet, and it will be these additions and not the field developments that will determine the

TABLE 3.—*Venezuelan Petroleum Imports and Exports Showing Relationship to United States Market*

YEAR	PRODUCTION CRUDE OIL BARRELS	PERCENT INCREASE OVER PRECEDING YEAR	EXPORTS CRUDE OIL BARRELS	PERCENT INCREASE OVER PRECEDING YEAR	(1) ESTIMATED CRUDE OIL ABSORBED BY U.S. MARKET BARRELS	(2) ESTIMATED ADDITIONS TO U. S. SUPPLY OF REFINED PRODUCTS RESULTING FROM VENEZUELAN EXPORTS BARRELS.			
						GASOLINE	PERCENT U.S. TOTAL	GAS AND FUEL OIL	PERCENT U.S. TOTAL
1917	20,000								
1918	333,000	77							
1919	424,000	36.5							
1920	457,000	7.8	280,000						
1921	1,078,000	135	1,013,000	260	24,000	3,000	.003	19,000	.008
1922	2,1[illegible]7,000	97	1,813,000	79	950,000	120,000	.08	760,000	.3
1923	3,700,000	76	3,295,000	81	1,200,000	150,000	.08	960,000	.3
1924	8,600,000	133	8,440,000	156	1,600,000	200,000	.09	1,280,000	.4
1925	20,000,000	132	19,000,000	125	8,200,000	1,000,000	.4	6,500,000	1.8
1926	36,000,000	80	33,464,000	76	30,000,000	4,000,000	1.3	24,000,000	6.6
1927	63,000,000	75	55,927,000	67	41,500,000	5,000,000	1.5	33,000,000	8.4
1928 (3)	106,500,000	66	98,000,000	76	75,000,000	9,400,000	2.8	60,000,000	14.3
TOTALS									

(1) THIS INCLUDES DIRECT IMPORTS OF CRUDE PLUS THE ESTIMATED EQUIVALENT QUANTITY OF CRUDE OIL REPRESENTED IN THE IMPORTS BY GASOLINE, FUEL OIL AND OTHER REFINED PRODUCTS

(2) ASSUMING THAT THE AVERAGE YIELD FROM VENEZUELAN CRUDE UNDER PRESENT REFINING PRACTICE IS 12.5% GASOLINE, 80% FUEL OIL AND GAS OIL

(3) 1928 FIGURES ESTIMATED

amount of oil that Venezuela will place on the markets of the world in 1929.

At the present writing, the plans for new tanker construction during 1929, are not known. What appears to be a reasonable expectation in this direction is an average increase for the year of about 15 per cent. in the total fleet capacity; and this in turn points to total exports for 1929 of around 138,000,000 bbl. Production will be larger by at least 10 per cent., and probably in view of the large volume of new steel storage projected and under construction, the increase may be nearer 15 per cent. Assuming the latter to be the case, production for the year may be estimated at 160,000,000 bbl., of which the significant figure from the viewpoint of American oil interests is the 138,000,000 bbl. that will be exported.

In most discussions and writings relative to the Venezuelan situation, the figures customarily presented are for field production, and in many

cases insufficient emphasis is given to the fact that only the oil exported has a direct bearing on the price structure in the United States. Even an export figure such as the foregoing estimate of 138,000,000 bbl. conveys little to a person only casually conversant with world-production statistics. Accordingly, it will be of interest to observe this present production and export situation in relation to its own past record, together with a comparative measure of its quantitative importance with respect to the United States market. In Table 3, the entire oil production and export record of the country is given, together with the percentages of annual increase, and for the last 8 years an approximation of the volume of exports coming to the United States.

It should be noted that this estimated amount of crude "consumed in the United States" includes not only the amount of crude petroleum imported but also an estimate of the amount of Venezuelan crude required to furnish the refined products that reached the United States from Venezuela and the Dutch West Indies. The monthly import figures published by the United States Department of Commerce, from which this table was in part prepared, show the quantities of crude petroleum and refined products imported into the United States from Venezuela, but the conversion of these refined products into terms of crude involves an estimate of the refinery accomplishment which may not be entirely accurate. It is believed, however, that the assumption made (*viz.*, an average fractionation into 12½ per cent. gasoline and 80 per cent. gas oil and fuel oil) does not introduce into the table an inordinate percentage of error that could materially change the general comparison.

An inspection of this table shows that the great bulk of Venezuelan exports gravitates to the United States. There is, however, a substantial difference between the amount of crude produced and the amount actually imported into our country; as, for example, for the year 1928, when the production for Venezuela amounted to 106,500,000 bbl., of which it is estimated that 75,000,000 bbl. were consumed in the United States.

A further analysis of the import figures will reveal the fact that so far as the price of gasoline is concerned, the Venezuelan developments can have had little effect. The total gasoline from Venezuelan crude that came on the American market during 1928 probably amounted to less than 9,500,000 bbl.; say only 2.6 per cent. of our total refinery output.

With fuel oil the situation was quite different, as of this commodity the Venezuelan importations accounted for approximately 60,000,000 bbl., or 14.3 per cent. of the estimated American total. Without doubt the substantial increase in fuel oil available from Venezuelan crude largely contributed to the drop in price from $1.75 at the beginning of 1927 to $1.05 per bbl. for Bunker C grade (New York Harbor) at the close of 1928. The increasing importance of the relationship between Venezue-

lan production and the fuel-oil situation in the United States is clearly shown in the table. The effect on prices during the present year cannot be accurately forecast at this early date. Important refinery construction is now in progress in the Caribbean area, and certain far-reaching changes in the export situation will result therefrom. In general, it may be stated that a larger percentage of Venezuelan exports will reach the American market as gasoline, and the volume of fuel oil may be but slightly increased.

DISCUSSION

H. J. Wasson.—I am inclined to think, after having seen some later government figures, that the estimate for gasoline (9,400,000 bbl.) in Table 3 is probably too low. I arrived at that figure by taking the actual imports of gasoline from Venezuela as gasoline, which were about 2,500,000 bbl., estimating the extraction of gasoline which came into the country as crude, and adding the two together. I took 12.5 per cent. as an average factor for gasoline recovery, not knowing how much of the oil was refined on a straight-run basis and how much was cracked. I am inclined to think now that more of it was cracked than I allowed for. Some fuel oil from straight-run operations was later cracked, so the amount of gasoline which the American market had to absorb in 1928 was no doubt more than here shown. Probably the estimate should be raised to about 12,000,000 bbl. That would raise the 1928 figure to 4 per cent. of the total supply. This still is not a very big proportion of our total domestic supply.

The same thing is true of the figure for fuel oil. This is probably a little too high, but if it is reduced to 50,000,000 bbl. it still constitutes say 9 or 10 per cent. of the total United States supply. That probably has been enough fuel oil to cause the declining price trend for this commodity which we have all seen in the last two years. Fuel oil prices have declined from $1.75 f.o.b. New York, at the beginning of 1927, to a current price of $1.05.

These import figures of gasoline and fuel oil are closely related to another one of the very important topics before the industry—the agitation for a tariff. This table does not tell the story, but the recent figures released by the U. S. Bureau of Mines provide data bearing on that question. The figures are about as follows: In 1928, we ran to stills 74,000,000 bbl. of foreign oil. We imported directly into the country 4,200,000 bbl. of gasoline. We can take that 74,000,000 bbl. and apply some appropriate factor to it and find out how much gasoline from this source was added to our domestic supply.

In this case, taking 20 per cent., which I believe is fair, considering that it is mostly heavy oil, we get 14,800,000 bbl. of gasoline from the foreign crude, refined in our country, which with the 4,200,000 bbl. imported as gasoline makes 19,000,000 bbl. The same government figures for 1928 show that we exported 53,000,000 bbl. of gasoline during the year; so that our exports were more than twice as much as our imports, actually a very satisfactory trade balance in our favor, of 24,000,000 bbl. of gasoline.

My feeling on this question is that if a larger number of people who are talking about and agitating tariffs would familiarize themselves with these figures, many would desert the pro side of the case, because it clearly seems to be based on unsound premises.

We estimated 160,000,000 bbl. production in the field during 1929, of which about 138,000,000 bbl. will be exported. That seems a large increase, although it is much less proportionately than has been the year to year increase heretofore. However,

there are so many factors entering into this estimate that I doubt whether we can be very certain about it. It will depend on the policy of the operators, about which no one knows but themselves.

Something like this might happen: If the Atlantic Seaboard market during the present year about holds its own, or does not fall very much below the present levels, we can reasonably expect some such increase as we have estimated. If there is much distress crude and distress refined products in the eastern market, I doubt whether the Venezuelan operators would force their sales to this extent. In other words, they would not force their sales in competition with oil that was being severely liquidated. In that case, the imports into the United States might not change greatly over what they were during 1928.

A. R. Denison,* Fort Worth, Tex.—I should like to draw a comparison between Venezuela and a Mid-Continent area. The Venezuelan production is essentially in a basin, or geosyncline, comprising a geologic unit. From 1224 wells, a total of 243,000,000 bbl. has been recovered. In the West Texas Permian Basin, also a geologic unit, from 2000 wells, slightly more than 193,000,000 bbl. has been recovered.

What is the character of structure at El Mene, which has such high-gravity oil? Does it occur in the same age of beds and under the same structural conditions as the pools on the lake shore?

H. J. Wasson.—I do not know exactly the structure at El Mene. The general impression is that it is anticlinal, but the depths of the wells certainly do not indicate it. However, it is entirely different from the long monoclinal strip along the east side of the lake. Possibly it is an accumulation against a fault plane.

J. E. Pogue,† New York, N. Y.—In the past two months the rate of production in La Rosa field has been declining, December less than November, and January still less. Is that an artificial factor or does it represent the probable peak of that particular pool?

H. J. Wasson.—I am sure that that is due to the fact that during the last few months drilling was concentrated in Lagunillas. The several companies moved a number of drilling rigs down there and speeded up their operations in Lagunillas, leaving La Rosa more or less to go along in its own way without much drilling. It is thus erroneous to consider that La Rosa has reached a peak or anything like it. The reaching of such a peak is a matter of how many wells the operators want to drill. At La Rosa, in the inland territory, there is a very substantial undrilled proved area of territory, completely surrounded by producing wells, and the same is true out in the water in the other direction. If the operators wanted to double their drilling campaign, they could raise the peak away above what it ever has been in the past.

J. E. Thomas, Fort Worth, Tex.—I am simply astounded by Mr. Wasson's estimate of the amount of oil Venezuela will supply this year. Is his estimate of 160,000,000 bbl. based upon the amount of oil that they are required to produce, due to the exigency of their drilling program or is it the amount of oil that he estimates they have a desire to sell? Does he think that amount of oil will be produced and imported against an average price of American crude less than last year's average price?

H. J. Wasson.—That is a difficult question. There is a factor in that situation which I did not mention. I should have said that the oil going out of Venezuela goes out in shallow tankers. Deep vessels do not come into the lake. That means

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† Consulting Engineer.

that the companies have a tremendous investment in that fleet, which numbers about 70 vessels at present, and we know from the records of shipyards that there are certain other vessels now under construction. Possibly that fleet will be increased by 15 per cent. during the coming year. I am satisfied that the companies are not going to lay up any of these vessels; that they are going to work them at 100 per cent. efficiency. The capacity of this fleet then gives the limits of the figure of exports; add 10 or 15 per cent. to that and you have the field production.

There is also a big storage-construction campaign under way in Venezuela. Some of the companies are building numbers of 80,000-bbl. tanks. That is going to absorb another 10,000,000 bbl. or so in 1929 that will not be exported. This oil will be counted to the field production. So I will stand on the estimate of 138,000,000 bbl. exports, unless some cataclysmal calamity happens to the market where this oil is being sold. In that case, I do not think the Venezuelan operators will force competition beyond the point at which they can make a profit.

However, I believe that their low costs will yield them a profit in the Atlantic seaboard market on a basis away below the basis that will yield a profit to any of the high-cost oil in the United States, California or the Mid-Continent. Of course there will always be some low-cost oil in California and Mid-Continent that can compete with Venezuelan oil any place in the world, but I should say offhand that 80 or 90 per cent. of it will not be able to compete if the Venezuelan operators force the issue.

J. E. Thomas.—I would like to reverse Mr. Wasson's figures. It is 80 or 90 per cent. of our overproduction that can compete with Venezuela. That is exactly the point that Venezuelan operators overlook. The Yates pool can produce 150,000,000 bbl. at a total operating expense of less than 8 c. per barrel.

H. J. Wasson.—How many barrels of oil will come under the head of that low-cost oil? You have millions of dollars tied up in leases. All this money is charging interest and should be applied to your cost. Also add your unsuccessful wildcat wells to the cost. One company in Venezuela has drilled two hundred wells, more or less, without being required to drill a single wildcat well in the past 2 years. They have a different order of cost entirely. It is almost the same as in Persia; they practically turn on a tap and get all the oil they want.

C. W. Hamilton* New York, N. Y.—I would like to offer a slight revision in the figures of shipment and production proposed for Venezuela during 1929. As Mr. Wasson has indicated, shipments, that is, exports from the country, are controlled by the capacity of the coastwise fleet taking oil out of Lake Maracaibo. That is our transportation, our pipe-line system. From all known records of boats built and being built, the exports for 1929 will be more nearly 130,000,000 than 138,000,000. In addition, there are the runs to the local refineries. There is built and in operation at the present time, refinery capacity for approximately 18,000 bbl. and a 1200-bbl. plant is under construction. Refinery runs plus runs to storage, now built or contemplated during 1929, will increase the total production from the 130,000,000 figure for exports to approximately 141,000,000 for the year.

J. E. Thomas.—I think that is probably nearer the way it will turn out.

H. J. Wasson.—Will that 20,000,000 save the situation?

J. E. Thomas.—No, but it will have a tendency to reduce imports or will have forced those lower prices.

* Venezuela Gulf Oil Co. and South America Gulf Oil Co.

A. R. DENISON.—I might answer a question, in part at least, which Mr. Wasson raised regarding low-priced crude produced in the United States. In Texas, for example, we produced some 255,000,000 bbl. of oil last year. About one-half of that was produced in the Permian Basin and brought a price of 65 cents.

E. L. ESTABROOK,* New York, N. Y.—It is hardly correct to talk about costs of production in Venezuela as being extremely low. Actually Venezuelan costs can be more properly compared to California than to West Texas costs. In the operations on Lake Maracaibo we have to spend about $10,000 on a foundation and platform before we can begin to erect the derrick. Instead of producing clean oil from limestone reservoirs we must carry on a continual battle against soft sand. The wells must be watched and nursed along. Even while the wells flow, our lifting costs are comparatively high, for our lease men cannot walk or drive a Ford from well to well; they must be conveyed in a substantial launch with a crew of one or two men. The cost is comparable to that of sending a roustabout around the lease in a Cadillac car with a liveried chauffeur. A comparison of Venezuelan costs with California has considerable justification in other ways. In California deeper wells are drilled but higher grade oil is obtained while the extra cost of the deeper wells is more or less balanced by our cost of foundations in the lake. In addition, we have the extra cost of serving these wells when all transportation must be over water. This involves not only costly transportation equipment but comparatively slow movement and often the actual inability to carry on the work because of rough water.

C. W. HAMILTON.—Comparison of West Texas with Venezuela assumes that the production costs in Venezuela are comparable to those of West Texas. It seems to me that transportation cost rather than production cost is the answer to the problem. Perhaps some one can tell me the comparative cost of transporting West Texas crude and Venezuela crude to the Atlantic seaboard?

W. A. SINSHEIMER,† New York, N. Y.—The tariff from West Texas, including gathering and loading, to the United States Gulf ports at Houston or Texas City is approximately 63 c., and I understand that the tanker rate from Texas City to New York is approximately the same as the tanker rate from Venezuela to New York.

J. E. POGUE.—On that basis, the Venezuelan oil delivered is lower in cost than any other available to the eastern seaboard. It seems to me that in this whole problem of the law of supply and demand not enough attention has been given to the cost of production.

N. E. ODELL,‡ Cambridge, Mass.—Are there geophysical explorations going on at present near Maracaibo?

H. J. WASSON.—Some have been carried on for the past year or two and some are going on at present. The bulk of the basin area surrounding the lake is low, flat-lying land, and there are few outcrops. This makes it necessary to locate new oil fields either by luck or by geophysical methods, and the geophysical methods are now being used rather extensively.

* Consulting Petroleum Engineer, Pan American Petroleum & Transport Co.
† Henry L. Doherty & Co.
‡ Harvard University.

Mexican Oil Fields during 1928

By Valentin R. Garfias* and R. V. Whetsel,* New York, N. Y.

(New York Meeting, February, 1929)

Mexican petroleum production for 1928 was approximately 50,000,000 bbl., the lowest in 12 years, showing a decrease from 1927 of over 14,000,000 bbl. The steady downward trend for the past 7 years has allowed Russia to outrank Mexico by a wide margin for third position and if the expected decline continues during 1929 it should place Persia ahead of Mexico as fourth in rank.

The year 1928 was characterized by a continuation of the reentrenchment previously begun by the oil industry in Mexico in an attempt to adjust itself to the adverse conditions caused by the steady depletion of the fields, the rapidly increasing competition from Venezuela and the United States and the as yet unsettled petroleum legislation and taxation situation. With the exception of the Isthmus of Tehuantepec, drilling in proved fields was considerably curtailed and although the number of wildcats completed exceeded those of the previous year, no extensive drilling programs were undertaken. Practically without exception, the major companies reduced personnel and operations to a point where they could meet existing conditions and mark time while awaiting a more stable basis for the future testing of unexploited regions. Many terminal and transportation facilities were abandoned during the year.

Development

Only 371 wells were completed during 1928, as against 583 in the previous year and 808 during 1926, and although the percentage of producers in 1928 was 34 per cent., compared to 26 per cent. in 1927, the initial production of wells was considerably lower than during the previous year, a great number of the wells showing salt water and becoming "strippers" from the time they started to flow. Development is summarized in Table 1.

Drilling in the Northern fields did not prove any new pools of importance, the most successful wells being located in the old producing areas of Cacalilao, Panuco and Topila. (Fig. 1.) Very few of the producers made more than 1000 bbl. daily, and a great many less than 300 bbl. a day.

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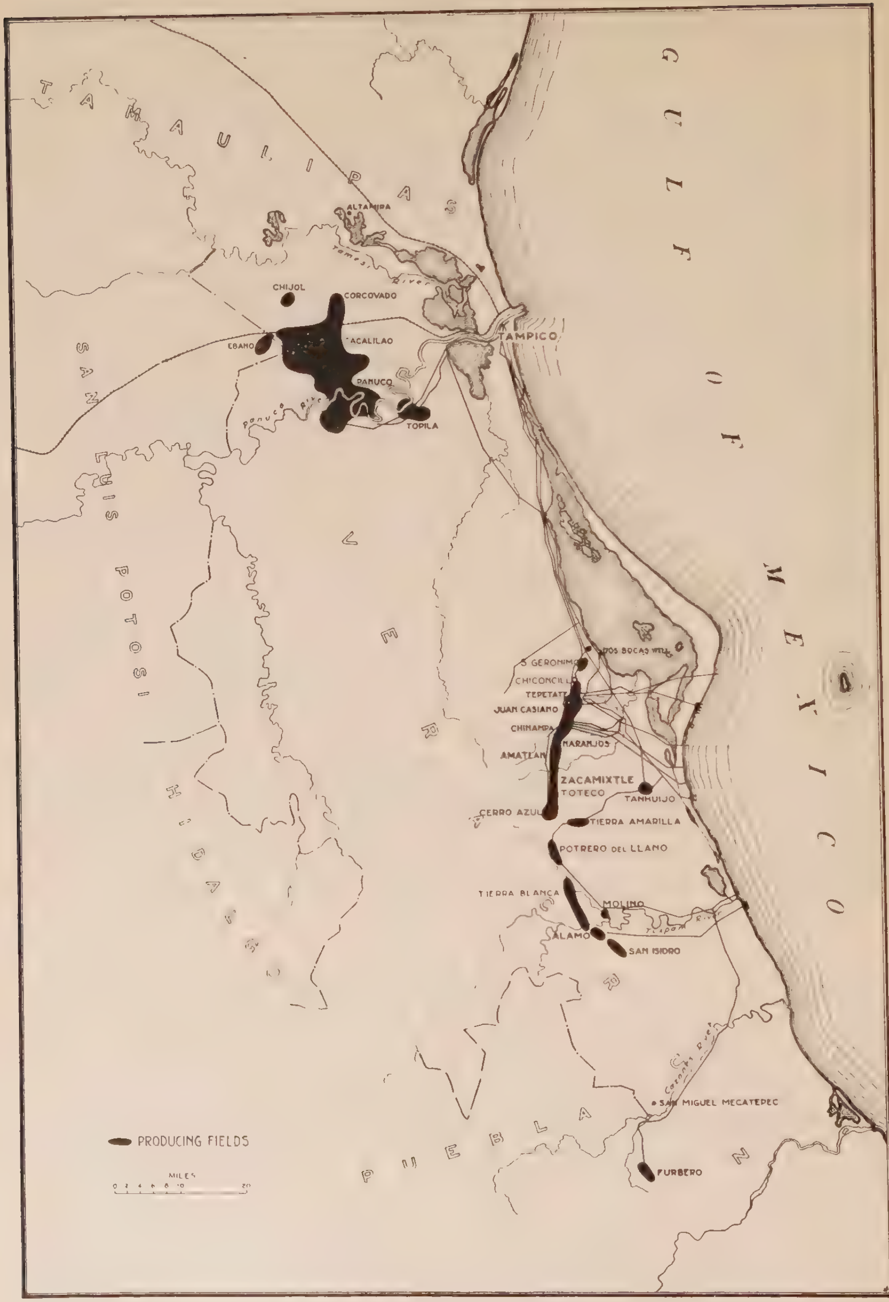

FIG. 1.—MAP OF MEXICO SHOWING PRODUCING FIELDS.

TABLE 1.—*Petroleum Development in Mexico*, 1928

	Failures	Producers	Total
Northern fields			
Panuco	44	34	78
Topila-Caracol	33	17	50
Chapacao-Corcovado	8	2	10
Salinas	12	1	13
Cacalilao	51	17	68
Limon	7	0	7
Altamira	7	0	7
Quebracha	2	0	2
Total	164	71	235
Southern fields	43	28	71
Isthmus of Tehuantepec	23	28	51
Wildcats	13	1	14
Grand total	243	128	371

Results in the outlying districts of the Northern fields, such as Limon, Altamira and Quebracha, were very discouraging, and not one well could be termed a commercial producer. Drilling in Salinas and Corcovado resulted in only three small "strippers" out of 23 wells drilled, and at the end of the year there was not a promising extension of the Northern fields in sight.

In the Southern fields only 46 wells were completed along the flooded portion of the "Golden Lane" from Dos Bocas to Alamo, and of this number 15 were small "strippers" and the remainder dry or salt water wells. Drilling was quite active in the southern extension of the Dos Bocas-Alamo fault from Alamo to San Isidro and of the 25 wells drilled, 13 were producers, a few of which were rated at 5000 bbl. a day. It was necessary, however, to handle carefully these wells, as salt water soon appeared if the flow was not restricted. None of the wells drilled further extended the Dos Bocas-Alamo fault southeast of San Isidro. Two unsuccessful tests were made in the Tamiahua Lagoon in an effort to extend the Dos Bocas-Alamo fault to the North.

Perhaps the outstanding feature during the year was the completion of a producing well in Mecatepec, located in wildcat territory about 10 miles north of the old Furbero field and 30 miles south of Alamo. The well encountered an initial flow of about 7000 bbl. daily at a depth of 3608 ft., but by the end of the year there had not been sufficient additional development to determine whether or not the well had discovered an important new pool.

A total of 14 wildcat wells were completed during 1928, which was twice the number of the previous year, but, with the exception of

the Mecatepec well, all were failures. A dry hole was completed in granite at a depth of 3314 ft., near San Marcos in central Coahuila, and another interesting dry test was drilled to a depth of 4782 ft. near Zambrano in northern Coahuila not far from the United States border. Two dry holes were drilled in Chocoy north of Altamira, and another on Magascatsin west of Chocoy. Eight tests were made north and west of the Dos Bocas-Alamo fault in the south field, all of which were unsuccessful.

The Isthmus of Tehuantepec showed a big increase in drilling activity in 1928, 51 wells being completed as against 24 in 1927. A total of 38 wells were drilled in the Filisola field and other proven areas, 23 of which were small producers. The additional production of these wells was sufficient to hold the daily average of the fields to approximately 7000 bbl. throughout the year. A total of 13 wells was drilled in extensions of the proved area, five of which were producers. At the end of the year 9 wells were drilling in the Isthmus region.

Production

Table 2 shows production in 1928 as compared with that of the previous year:

Table 2.—*Petroleum Production in Mexico,* 1927 *and* 1928

Fields	1927, Bbl.	1928, Bbl.	Decrease, Bbl.
Northern (12° Be.)	38,900,000	25,553,000	13,347,000
Southern (21° Be.)	22,600,000	22,032,000	568,000
Isthmus of Tehuantepec (32° Be.)	2,700,000	2,415,000	285,000
Totals	64,200,000	50,000,000	14,200,000

The production of the Northern fields declined steadily in all the pools throughout the year from 80,000 bbl. daily in January to 58,000 bbl. in December. During January, 1928, the daily average production per well was 124 bbl., and in December only 95 barrels.

The production in the Southern fields declined from 67,000 bbl. daily in January to 50,000 bbl. in December. At the beginning of the year, new wells in the southern extension of the Dos Bocas-Alamo fault from Alamo to San Isidro promised an increased production of light crude during 1928, but serious salt water invasion in this area during March and April greatly depleted the flow of the larger wells. Production in the older pools from Tepetate to Alamo declined steadily throughout the year.

In the Filisola field located in the Isthmus of Tehuantepec, production was maintained at an almost constant level, the production of old wells declined, but the addition of several small producers maintained

the production to approximately 6500 bbl. daily, which was increasing slightly toward the end of the year.

Oil in Storage

Actual figures of oil stocks in Mexico were not available at the end of the year, but estimates from consumption, exports and production show that approximately 1,000,000 bbl. were added to Mexican storage during 1928. Heavy crude stocks increased about 2,000,000 bbl., while light crude storage decreased 1,000,000 bbl. There was but little change in the stocks of other grades.

Table 3 shows oil stocks by grades on Jan. 1, 1928, and the estimated storage on Jan. 1, 1929:

Table 3.—*Mexican Oil Stocks, Jan.* 1, 1928 *and* 1929

	Jan. 1, 1928, Bbl.	Jan. 1, 1929, Bbl.
Heavy crude (12° Be.)	4,600,000	6,500,000
Light crude (21° Be.)	3,000,000	1,700,000
Topped (17° Be.)	5,100,000	5,700,000
Refined products	1,100,000	900,000
Totals	13,800,000	14,800,000

Mexican Government reports show that in 1927 there were 2296 steel tanks in Mexico with a total capacity of approximately 60,000,000 bbl. These figures include many terminals and stations that have been abandoned, and it is probable that steel tanks now in condition to store oil have a total capacity of not over 25,000,000 barrels.

Imports

During 1927 one of the major companies engaged in refining in Mexico and producing in Venezuela, imported Venezuelan crude for refining purposes. By the beginning of 1928, however, imports of crude had entirely ceased, and the only imports were small amounts of gas oil into Tampico and Vera Cruz, and small shipments of gasoline and lubricants into the west coast and across the United States border.

Exports

The decrease in exports during 1928 was greater than the decrease in production, totaling approximately 36,000,000 bbl., or 16,000,000 bbl. less than the previous year. Heavy crude exports decreased 8,000,000 bbl. and fuel oil shipments were less than one-half of 1927 exports, or 7,000,000 bbl. For the first time in 3 years light oil exports increased, totaling over 1,000,000 bbl. The export of refined products in 1928 also increased, being 1,000,000 bbl. greater than during the previous year. Exports in 1928 are shown in Table 4.

Table 4.—*Exports of Mexican Petroleum, by Grades,* 1928

	Bbl.
Heavy crude (12° Be.)	18,800,000
Fuel oil (17° Be.)	7,000,000
Light crude (21° Be.)	1,100,000
Distillates	5,100,000
Asphalt	1,800,000
Bunkers	2,200,000
Total	36,000,000

Exports to the United States aggregated approximately 26,000,000 bbl., or about 73 per cent. of the total, while during 1927 they totaled 36,000,000 bbl., or about 70 per cent. of the shipments for that year. Shipments to Cuba, West Indies and South America were about 4,000,000 bbl. less than during the previous year. Exports to Europe were also less than in 1927. Grades of oil shipped to the United States consisted mostly of heavy Panuco crude and fuel oil, while the greater part of those to other countries were distillates and other refined products.

During 1928 further abandonment of sea-loading terminals on the Panuco River took place and at the close of the year 95 per cent. of the oil shipped from Tampico was loaded out of only six terminals.

Domestic Consumption and Refining

Domestic consumption for 1928 is estimated at about 12,000,000 bbl., or about 2,000,000 bbl. less than the previous year, of which approximately 7,500,000 bbl. went to interior consumption and the balance for local field use. The decrease in domestic consumption was due largely to curtailment of operations in the fields and terminals. Table 5 is an estimate of domestic consumption by grades, for 1928, based on the distribution of domestic consumption for the previous years.

Table 5.—*Domestic Consumption of Mexican Petroleum,* 1928

Grade	Local Field and Operation Consumption, Bbl.	Railroad, Automobile and Interior Consumption, Bbl.	Total, Bbl.
Light crude	200,000	10,000	210,000
Heavy crude	1,300,000	2,000,000	3,300,000
Gasoline	50,000	1,000,000	1,050,000
Kerosene	40,000	250,000	290,000
Gas oil	1,300,000	100,000	1,400,000
Fuel oil	1,100,000	4,000,000	5,100,000
Lubricants	10,000	100,000	110,000
Other products	500,000	40,000	540,000
Total	4,500,000	7,500,000	12,000,000

Oil refined in Mexico was approximately 6,500,000 bbl. less than the previous year, or about 25,700,000 bbl. It is of interest to note that

despite the big decrease in the amount of crude run, the output of distillates and other refined products was over 10,000,000 bbl., or greater than last year, while the amount of fuel oil turned out by refineries was over 7,000,000 bbl. less than in 1927. There was a large decrease in the amount of heavy crude run through domestic refineries.

At present there are but two large refineries and one small unit operating in Tampico, which, with the plant at Minatitlan that runs the light oil production of the Isthmus of Tehuántepec, are the only refineries operating in Mexico. Table 6 is an estimate of the quantities of crudes run through refineries and products obtained during the year.

TABLE 5.—*Statistics of Mexican Refineries*, 1928

CRUDE OIL REFINED	BBL.
Oil refined	
Heavy (12° Be.)	1,400,000
Light (21° Be.)	21,900,000
Isthmus of Tehuantepec (32° Be.)	2,400,000
Total	25,700,000
Refined products	
Fuel oil (17° Be.)	14,300,000
Distillates and other refined products	10,400,000
Losses, etc	1,000,000
Total	25,700,000

MARKET CONDITIONS

At the close of 1927 the rapid increase of Venezuelan production and the overproduction in the United States began to affect the market for Mexican crudes, especially the heavy Panuco crude of the Northern field, and by the middle of the year the price of Panuco crude had fallen to $1 per bbl. f.o.b. ship, the lowest figure in four years. Notwithstanding the rapid decrease in Panuco crude production, its price continued to decline and by the end of the year spot cargoes were selling in Tampico for 90 c. f.o.b. ship.

In the Southern field or light oil district two companies were sole buyers and transporters of this grade of crude. Throughout the year small independent producers received from 50 c. to 60 c. per bbl. at the well, the price of this grade of crude (21° Be.) being less than that offered for the heavy Panuco crude (21° Be.) in the Northern fields.

Production in the Isthmus of Tehuantepec is controlled by one company and is utilized by its refinery at Minatitlan in the State of Vera Cruz.

The Mexican domestic market continued to be controlled chiefly by the two companies operating refineries in Mexico. Other companies imported small amounts of gasoline and lubricants from the United States in tank cars and succeeded in creating some competition to the local

refiners, especially near the United States border and along the west coast of Mexico.

Because of insufficient production from their own wells, the National Railways was forced to purchase the greater part of its supply of fuel oil from outside producers.

Taxes

Table 7 shows the variation of rates of taxation on oils exported, in dollars per U. S. barrel.

TABLE 7.—*Mexican Oil Tax Rates, September,* 1927 *and* 1928

Grade	Taxes, Dollars per Bbl.	
	September, 1927	September, 1928
Heavy crude (12° Be.)	$0.17	$0.14
Light crude (21° Be.)	0.31	0.22
Fuel oil (17° Be.)	0.27	0.19
Gas oil	0.36	0.28
Refined gasoline	0.25	0.27
Crude gasoline	0.50	0.54
Refined kerosene	0.14	0.16
Crude kerosene	0.27	0.30
Lubricants	0.29	0.29

As the taxes are based on price quotations of oil in the United States, the tax figures for September, 1928, on crudes, fuel oil and gas oil are somewhat lower than for September of the previous year, although the decline of the selling price of the Mexican heavy crude, for instance, has been more pronounced than the reduction in taxes. The figures in Table 7 do not include minor taxes which aggregate approximately 2 c. additional per barrel.

Table 8 gives the total yearly taxes paid to the Mexican Government on oil shipped from Mexico since 1919. These figures do not include minor taxes of approximately 2 c. per bbl. which aggregate about $20,000,000 additional.

TABLE 8.—*Oil Taxes Paid to Mexican Government,* 1919–1928

Year	Taxes
1920	$ 22,740,000
1921	31,562,000
1922	42,990,000
1923	30,268,000
1924	27,311,000
1925	21,072,000
1926	17,411,000
1927	9,512,000
1928 (estimated)	6,000,000
Total	$208,866,000

During the latter months of 1928 a tax discount was being considered on oil produced from new zones at a given distance from the sea coast in order to encourage development in new territory in the face of competition from other countries like Venezuela, with little or no taxation, but the year closed without a final agreement on the amount of tax discount or the exact limits of the new zones.

A reduction of approximately 35 per cent. on personal income taxes affecting wages, salaries, etc., was made effective in January, 1928, thus reducing the prohibitive tax rates on personal incomes that were established in August of the previous year.

Outlook for 1929

A careful analysis of the various factors affecting the industry in 1928, shows that these will continue to be effective through 1929, and that they will be felt possibly throughout 1930. It is very probable, therefore, that the present policy of curtailed development will continue during 1929. Development on the Isthmus of Tehuantepec may increase on a small scale and some increased activity may result in Mecatepec should wells drilling in the vicinity of the discovery well prove a more extensive pool, but in the old pools of the Northern and Southern fields production should continue to decline because of the rapidly decreasing productivity of the wells, the low prices received for the production and the high taxation as compared with practically tax-free oil from competitive fields like Venezuela.

It is probable that wildcatting may increase slightly in 1929, and that exploration in new territory will go ahead on a very conservative basis until pending questions relating to taxation and the new petroleum law are settled and it can be seen that Mexican oil can be produced at a profit, in competition with other fields.

Any estimate of production from Mexican fields for a year in advance is hazardous, and it must be kept in mind that such estimating has for its basis the past producing history of the fields and the present status of development and production as well as the general conditions influencing them. With such limitations in mind, it is estimated that production in Mexico for 1929 will be about 10,000,000 bbl. lower than in 1928 The production of heavy oil for 1929 should, therefore, be about 19,000,000 bbl., a decrease of over 6,000,000 bbl. in 1928, and the output of light oil about 17,500,000 bbl. for 1929, or 4,000,000 bbl. less than the previous year. Production of the Isthmus of Tehuantepec should aggregate about 2,500,000 bbl., bringing total estimated production for Mexico to approximately 39,000,000 barrels.

These estimates do not take into account the possibility of new pools such as Mecatepec, which may account for wells of large initial production.

Oil Developments in Colombia in 1928

By James Terry Duce,* New York, N. Y.

(New York Meeting, February, 1929)

No important producing developments took place in Colombia during the year 1928. This was at least partly due to the paralysis of operations by the passage, during the latter part of 1927, of a law which was regarded by the oil companies as confiscatory and unjust, and the promulgation of exceedingly stringent regulations of this law under decree No. 150, published Jan. 28, 1928. This decree, which contained 24 articles, practically prevented not only producing operations by the oil companies but even such activities as geological explorations and surveying, as severe fines were imposed for the possession of maps not registered with the Ministry of Industries. Both this regulatory decree and the law were subject to attack in the courts by several of the oil companies. The regulatory decree was suspended May 22 by Presidential proclamation, until the suits against it are decided by the Supreme Court and Council of State.

Though another law was introduced into the Colombian Congress at a later date, no action was taken on it, and at the time of the writing of this paper, it would appear that no oil bill will pass the Colombian Congress during the present session.

The Barco concession, which was revoked in February, 1926, still continues an unsettled matter, although there have been rumors that the government was attempting to come to some decision on this rather difficult question. A hopeful sign toward the close of the year was the settlement of negotiations with the Tropical Oil Co. over the acceptance of the payment for royalties due the government from that company. This settlement, which covered a royalty on crude oil produced from June 30, 1926 to June 30, 1928, represented a cash payment for approximately 3,000,000 barrels.

It is to be hoped that during the coming year the Colombian government will see its way clear to clarify its position on petroleum legislation. A good augury for the future was the statement made by President Abadia Mendez on New Year's Day, in which he courageously admitted the errors of previous legislation and said, regarding oil, "Very soon

* Geologist, The Texas Co.

legislation on this subject will clearly define and guarantee the rights of all on the basis of a religious respect for private property and the exploitation of the legitimate reserves of the state without the fear of such odious exactions in the way of fiscal regulation as will dry up the spring from which flows this wealth."

The Colombian government should realize that an oil industry that will bring revenue to the country cannot be built up without the passage of such legislation as will guarantee to the oil companies investing money in such developments, reasonable security of tenure of the properties that they may acquire, and reasonable freedom from governmental interference. It can well afford to do this without losing, in any way, its police power, and at the same time it will profit materially by the growth of an industry that will bring into the country badly needed money.

The only producing company in Colombia during the past year was the Tropical Oil Co., which had produced 19,895,677 bbl. of crude oil up to December 31. The 1928 figures include natural gasoline production amounting to 198,879 bbl. for the first 10 months, or approximately 240,000 bbl. for the year. All of the natural gasoline is mixed with the crude oil, put through the pipe line and exported from Colombia.

The following refined products were produced at the refinery at Barranca Bermeja during the first 10 months:

	Barrels
Crude run	1,227,132
Gasoline	208,962
Kerosene	53,527
Gas oil	24,051
Fuel oil	928,112

The average daily pipe-line runs to the coast were 50,576 bbl.; the number of wells completed up to December 31 was 115, with an average initial production of 843 bbl. About 24 rigs were operated during the year. In addition to the companies mentioned, the South American Gulf Oil Co. was operating on the Leonard tract and on the properties of the Colombian Syndicate. On the Leonard tract at Las Monas at the close of the year this company was drilling three wells which stood at the last report as follows:

No. 1-A shutdown at 1587 ft.

No. 4 fishing at 3838 ft.

No. 5 drill stem stuck at 3456 ft.

On the Colombian Syndicate properties, it was drilling one well, Ordonez No. 2, which was shut down on December 11 at 106 ft. The only other active operating company at the close of the year was the Richmond Petroleum Co., a subsidiary of the Standard of California, which was drilling two wells, Galapa No. 1 at 3020 ft., and Repelon No. 1 at 1645 ft. Both of these wells had gas shows. The Magdalena Syndicate

closed down both its operations, at El Nato and Malpaso, after having small shows that were not of commercial significance. These wells were shut down at 2205 ft. and 3172 ft., respectively. The Lobitos Oil Co. abandoned its well in the Sogamosa district at 4273 ft. and withdrew from the country because of the oil legislation. A number of companies maintained some geological or legal staff within the country during the year. These included the Sinclair Oil Exploration Co., the Atlantic Refining Co., the D'Arcy Exploration Co., The Texas Co. and the Bogota Syndicate.

The author wishes to thank A. M. McQueen of the International Petroleum Corpn., William T. Wallace of the South American Gulf Oil Corpn., W. B. Heroy of the Sinclair Exploration Co., Michael O'Shaugnessy of the South American Oil Reports, and Samuel Haskell of The Texas Co., all of whom furnished information upon which this paper is based.

Developments in Bolivia in 1928

By Gilbert P. Moore,* New York, N. Y.

(New York Meeting, February, 1929)

Bolivia does not yet have any production which is being marketed. It does have a potential production, however, from wells which have been completed by the Standard Oil Co. of Bolivia, a subsidiary of the Standard Oil Co. of New Jersey. No other company is active in drilling and development work to date. The total potential production from wells now completed is about 6000 bbl. daily.

Wells Completed

Completions during 1928 and their initial daily productions, if any, were as follows: Camatindi No. 1, 350 to 1000 bbl.; Camiri No. 1, 500 bbl.; Sanandita No. 3, 100 bbl.; Tatarenda No. 1, dry hole, and Bermejo No. 2, deepened 50 ft. made 1000 barrels.

The most striking development of the year was the Camiri No. 1 well which, after just entering the sand, made 500 bbl. per day of 52° Bé. oil. This well is the northernmost good producer which the Standard has brought in to date. Oil from this well is used without refining in the tractors and trucks of the company. A small topping plant has been installed from which high-grade gasoline is obtained for use in motor cars and some is being produced for the use of air planes stationed at Villa Montes.

The results for Sanandita No. 3 were somewhat disappointing since Sanandita No. 2 was rated at about 3000 bbl. Tatarenda No. 1, located on a large unbroken structure, was drilled to 4000 ft. and abandoned as a dry hole.

Bermejo No. 2 was deepened 50 ft. to 2085 ft., and on a 10-day test averaged 1000 bbl. per day. This well is on the border between Bolivia and the Argentine.

Wells Drilling

The wells drilling are Camiri No. 2, Sanandita No. 5, Machareti No. 1 and Bermejo No. 5. This is the smallest number of drilling wells which the Standard has had for several years but is principally due to

* Geologist.

the number of recent completions from which the tools have not yet been moved. Bermejo No. 5 is expected to be a good well as it is located in a high position on the structure. Sanandita No. 5 is said to be lower on structure than the other Sanandita wells.

Holdings of American Companies

The Standard Oil Co. of New Jersey and the Bolivian Petroleum Corpn. are the only American companies now represented in the oil business in Bolivia. The Standard Oil Co. has reduced its holdings to slightly less than 1,000,000 hectares. About half of this area was selected from its original concession and the remainder was bought from different owners. It has all been consolidated into one concession.

The Bolivian Petroleum Corpn. which formerly held 1,250,000 hectares on the Altiplano has reduced its holdings to 375,000 hectares. Of the original holdings, 125,000 hectares were retained and 250,000 hectares were acquired to the east near the concessions of the Standard Oil Co. and along the route of the railway now under construction from Cochabamba to Santa Cruz. This company has done no drilling as yet.

Bolivian Imports

Bolivia imports crude oil and refined products to the value of approximately $1,300,000 annually and its imports are constantly increasing. The number of automobiles in the country is not great, but a large number is being imported each year. A big program of road building is now under way, the principal construction being to the east of the towns of Cochabamba and Sucre. Simon Patiño has proposed the building of a road from Cochabamba to the Chapare country, and this has been accepted by the Bolivian Congress. The construction of this road will give Patiño several concessions in the way of lands for colonization, water power rights over a large area, and oil rights over most of the Chapare basin.

Fuel oil retails for about $8.00 U. S. gold per bbl. in Bolivia and gasoline for $0.51 per gal. Most of this is supplied from Peru.

New Transport to Oil Fields

During the past year the railroad from the Argentine to Yacuiba, in Bolivia, has been advanced to a point some 9 miles from the Bolivian border. This has greatly facilitated the movement of drilling equipment and storage material to the eastern Bolivian fields. A system of motor roads has been completed which connects all of the camps of the Standard Oil Co. and trips which formerly took 15 days on muleback are now made in 2 or 3 days by automobile. These roads are not often used in the wet season due to the many streams to be crossed.

A regular passenger service by automobile from the end of the rails in the Argentine to Villa Montes and occasionally to Charagua has been established. Several independently owned trucks are doing heavy hauling for the Standard Oil Co.

The firm of Kennedy & Carey, of New York, was awarded the contract for the construction of the first section of the Cochabamba-Santa Cruz railway. This work is now under way and will be finished about April, 1930. The section will extend to Aiquile, some 200 km. in the direction of the eastern oil fields. From Aiquile an auto road is being built to Samaipata. This will eventually be extended to Santa Cruz and will connect up with the automobile road of the Standard leading south to Argentine.

It is also possible to reach these fields by airplane from Cochabamba. Weekly flights are made from Cochabamba to Santa Cruz and biweekly flights from Santa Cruz to Yacuiba. The first of the above mentioned flights takes about 2½ hr. The second is of about 4 hr. duration. Flights are made in Junkers monoplanes carrying two pilots and four passengers.

New Petroleum Legislation

For the past 2 or 3 years there has been talk among members of the Bolivian Congress regarding the necessity of revising the Petroleum Law of the country. This was brought to a head this year by the Minister of Industry who called a meeting on July 19, and appointed a committee to undertake the revision.

This committee practically rewrote the whole law. All of the vague phrasing of the articles retained from the present law was eliminated. Since the President of the Committee is a member of the Royal Spanish Academy of Letters, it is believed that the project of the new law is perhaps the most clearly and definitely stated of any law of the Latin-American countries.

Numerous changes were introduced into the law. Among the most important are the following:

The Republic of Bolivia was divided into four zones on the basis of existing transportation facilities and markets. The presence or absence of petroleum in these zones was not taken into consideration. Every 5 years a revision of the zones is to be made on the same basis as given above and new limits fixed for each zone.

The taxes in each of the four zones were established on a scale grading downward from 2½ centavos in the first zone to 1 centavo in the fourth zone. This is for the period of geologic exploration.

The size of concessions for exploration is graded upward from 100,000 hectares in the first zone to 400,000 hectares in the fourth zone.

The period allowed for geologic exploration ranges from 2 years in the first zone to 5 years in the fourth zone.

The deposit of guarantee of 10 centavos per hectare (approximately 3.6 c. U. S. gold) which is required on concessions for exploration under the present law is suppressed. The state received no revenue from this source as the interest on the money was paid to the depositor and it was believed that this was a stumbling block to the entry of national capital in the oil business. A registration fee grading downward from 1 centavo per hectare in zone 1 to 1/4 centavo per hectare in zone 4 was substituted for this deposit of guarantee. This fee will represent a small income for the Government and will probably cover the expense of the Registry Office.

The concessions for exploitation were divided into two periods. The first is the "Period of Preparatory Drilling" during which one well for every 50,000 hectares or fraction thereof contained in the concession must be drilled within a time limit ranging from 2 years in the first zone to 5 years in the fourth zone. The second is the "Period of Production" during which wells must be drilled at the rate of one per year for each 10,000 hectares or fraction thereof contained in the concession.

Concessions for exploitation may contain from 50,000 hectares in the first zone up to 200,000 hectares in the fourth zone. The time allowed for drilling the preparatory wells of the first period ranges from 2 years in the first zone to 5 years in the fourth zone. Taxes range from 6 centavos per hectare per year in the first zone down to 3 centavos per year in the fourth zone.

The deposit of 250 Bolivianos (about $90) for each 1000 hectares of the concession, as required under the present law, is suppressed and a registry fee substituted. This ranges from 5 centavos per hectare in the first zone down to 2 centavos per hectare in the fourth zone.

Concessions for exploitation are granted for a period of 50 years. This includes both the first and second periods.

During the "Period of Production" the taxes are graduated in a rising scale for the first 7 years. These taxes range from 10 centavos per hectare during the first year to 50 centavos per hectare during the seventh year and thereafter in the first zone, and 5 centavos per hectare during the first year to 25 centavos during the seventh year and thereafter in the fourth zone, to the fifteenth year when all zones pay 50 centavos per year per hectare.

Royalties to the state are 12 per cent. in zone 1, 11 per cent. in zones 2 and 3, and 10 per cent. in zone 4. A diminishing scale of royalties to the state is established for increased production, the percentage being gradually reduced as the amount of production increases until an output of 10,000,000 bbl. per year on the concession is produced when the royalty to the state is only 7 per cent.

The fixed minimum of production as prescribed by the present law is suppressed. This is a very good move as this clause is one of the most objectionable features of the present law.

Depreciation rates for various installations used in the oil industry are fixed at fair rates. The present law allows a maximum of only 10 per cent. on any sort of equipment and 5 per cent. on most of it.

A reciprocity clause is inserted in the new project of law as well as a clause stating that no concessions will be granted to either nationals or foreigners within 50 km. of the frontiers of the Republic.

The petroleum industry is classed as a public utility and may be expropriated by the Government for any reason.

The new law is thought to be a very fair one for both the Government and the oil industry. Certainly there is no other country in South America where it costs less to get started than in Bolivia. The new law was drafted with the idea of giving all possible encouragement for the entry of foreign and national oil companies. Until now Bolivia has been dependent on the tin-mining industry for its national income and it is believed that petroleum is probably its next best asset and should be developed as soon as possible. This new project of law has not yet been enacted. It has the approval of the Minister of Industry and by this time has probably been presented to Congress.

Probable Future of Bolivian Production

It is certain that Bolivian petroleum will not appear on any market during the next 10 years with the possible exception of the Argentine market. The Standard Oil Co. of New Jersey under its present contract with the Bolivian Government, is obligated to begin production Jan. 1, 1930. However, it is probable that this production will be held down to a minimum since the company has wells now producing in the northern Argentine from which crude oil and refined products can be supplied to the Argentine markets much more cheaply than from their scattered Bolivian wells.

The oil from the eastern Bolivian fields will be handled in one of two ways. Either pipe lines must be laid from the fields to points on the Paraguay River or the Bermejo River where tankers or barges can receive the oil for water transportation to Buenos Aires or a refinery must be built at railhead (Yacuiba) and only refined products shipped to the Argentine markets. The pipe line to water transportation would be comparable to that of the Andian National line in Colombia and probably of greater cost due to longer transportation of materials from the United States to Bolivia. The refinery would probably cost much less but for either mode of transportation, a large potential supply of oil must be in sight before such an operation could be undertaken with safety.

Bolivia presents no menace to the present world oil situation.

Oil Development in Peru in 1928

By A. M. McQueen,* Toronto, Canada

(New York Meeting, February, 1929)

Activity in the oil industry in Peru was somewhat above normal in 1928. Probably the most significant feature was the interest displayed in the oriental region in the northeast part of the country (Fig. 1). This region, though little known, has long been considered potentially rich in oil, gold, coal and other minerals, lacking only transportation to make it the country's most valuable source of income.

The Standard Oil Co. of New Jersey, through its recently formed subsidiary the Standard Oil Co. of Peru, has acquired various tracts along the Maranon and Ucayali rivers in the neighborhood of the Brazilian border. Standard Oil Co. interests have had geological and surveying parties in this part of Peru since 1921, and as a result of the work done, we understand they have under lease at the present time some 2,500,000 acres of prospective oil lands.

Development in the coastal region continued along normal lines during the past year. Production figures for both the International Petroleum Co. and Lobitos Oilfields show a small increase over the last few years. Total production figures since 1924 for the International Petroleum, Lobitos Oilfields and Zorritos companies, only in a minor degree estimated, are as follows: 1924, 7,924,700 bbl.; 1925, 9,138,042 bbl.; 1926, 10,750,676 bbl.; 1927, 10,110,696 bbl., and 1928, 11,969,677 barrels.

International Petroleum Co., Ltd.

Operations on the La Brea-Parinas Estate during 1928 continued with satisfactory results; nearly all branches showing improvement over the previous year. The average daily production for 1928 was 25,966 bbl., compared with 21,282 bbl. for 1927, an increase of 22 per cent. During the last two or three years, production methods on the company's property have been improved in line with the advance in scientific technique throughout the oil fields of the United States. Extensive investments were made in compressor equipment for handling surplus gas with the result that the gas-lift and repressuring operations are in no small way responsible for the increase in the 1928 production. In addition, the company's three casinghead plants produced 24,847,708 gal. of gasoline compared with 17,240,865 gal. in the previous year.

* Vice-president, Imperial Oil, Ltd.

During the past year the company increased its runs at the Talara refinery from 13,000 to 15,000 bbl. per day, and a new plant for the manufacture of lubricating oils is now being erected.

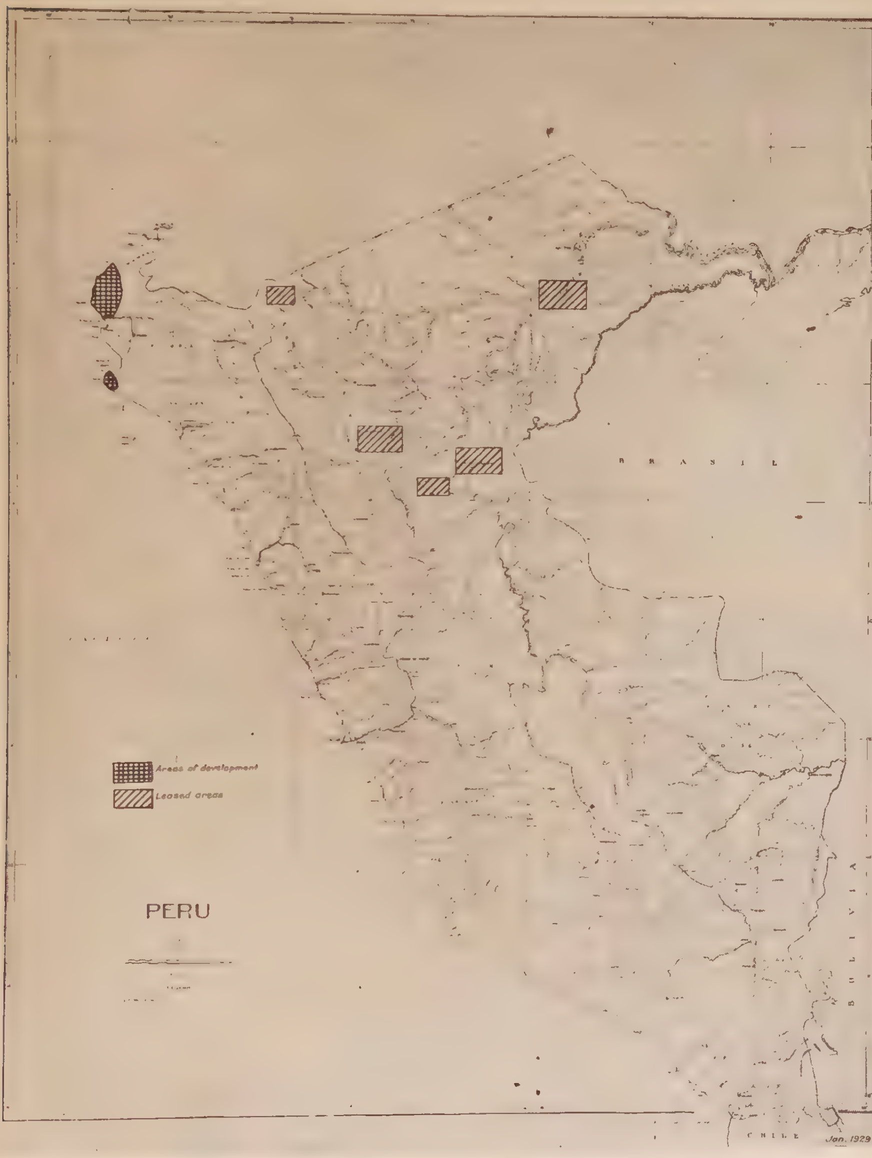

FIG. 1.—MAP OF PERU SHOWING AREAS UNDER DEVELOPMENT AND LEASED AREAS.

At Dec. 31, 1928, 2428 wells had been completed on the property, of which 1545 were producing oil or gas at that time. During the year

172 wells were completed, of which 147 were productive. These had an average initial production of 218 bbl. per day, compared with an average initial production of 189 bbl. per day for 138 productive wells completed during 1927. Footage drilled during the year was 326,238 ft., as compared with 274,448 ft. for 1927, reflecting a considerable increase in activity in this department. The following table giving comparative figures for the past five years is of interest.

	1924	1925	1926	1927	1928
Total footage drilled	201,765	152,592	270,231	274,448	326,238
Total wells completed	103	84	147	138	172
Producing wells completed	80	73	124	124	147
Average initial production, bbl.	204	344	222	189	218

Development work outside of the La Brea-Parinas Estate was marked by a conspicuous lack of success. A total of 12 wells were completed and abandoned during the year, five of these at Sechura, one at Tamarindo, three at Mancora, and three farther north toward Zorritos. The company now has 269,685 acres under lease and at the end of the year eight wells were still drilling. The year 1929 should definitely determine the advisability of continuing this work.

Lobitos Oilfields

The average daily production of Lobitos Oilfields increased from 6185 bbl. per day in 1927, to 6523 bbl. per day in 1928. The drilling statistics and potential production figures for this company are not available, but the writer is creditably informed that they have considerable production shut in.

Petroleum Production in Argentina

By José M. Sobral,* Buenos Aires, Argentina

(New York Meeting, February, 1929)

The approximate production of petroleum in the various fields and for the country as a whole is shown in the following table, the figures for the later months of the year being estimated.

Among the developments of the year may be mentioned the finding by the Standard Oil Co. of a small production, about 6290 bbl., at Aguas Blancas in the Province of Salta near the Bolivian border, and of about 88,000 bbl. at Lomitas, near Tartagal in the same province. The Government (Yaciementos Petroliferos Fiscales) in the last four months of the year also obtained about 6290 bbl. from Quebrada Galarce. The oil found in Salta is of good grade and while the quantity is small great hopes of larger production are entertained.

Approximate Total Argentine Production for 1928

	Barrels	Barrels
Comodoro Rivadavia	8,165,615	
Plaza Huincul	783,514	8,949,129
Distribution of Production		
Government, Comodoro Rivadavia	5,165,159	
Government, Plaza Huincul	306,166	5,471,325
Private, Comodoro Rivadavia	3,000,456[a]	
Private, Plaza Huincul	477,348[b]	3,477,804

[a] The companies represented are Astra, 649,474 bbl.; Oriente, 42,237; Ferrocarrilera, 1,337,380; Comp. Indust. y Comm., 609,092; Solano, 64,158; Diadema, 298,114.

[b] Standard Oil Co. and a few smaller companies.

Exploratory drilling has also been conducted around the Comodoro Rivadavia field. The Government is drilling at Vuela del Senguer south of Colonia Sarmiento and about 200 km. west of the main field but the prospect of success is not as yet large. The country around Castillo, where the Royal Dutch Co. has property, is regarded more favorably. Perhaps the most interesting event of the year was the discovery of a productive horizon at Comodoro Rivadavia about 200 m. below that previously exploited. This new horizon was found by the Ferrocarrilera Co. at 769 m. in its well No. 81, the previous yield for this

* Director, Dirección General de Minas Geologia e Hidrologia.

company being from 580 m. This discovery is considered to be of large importance and is all the more welcome in that the older horizon had begun to show signs of decline; that is, an increasing number of new wells required to be drilled in order to keep up production. The horizon found by Ferrocarrilera was also picked up by the Royal Dutch in the western part of the field. These discoveries indicate the desirability of deeper drilling throughout the field and in particular the testing of the whole section down to bed rock.

Persia and Iraq

By Sir John Cadman,* London, England

(New York Meeting, February, 1929)

The production from the Maidan-i-Naftun area for the year ending March, 1928, was 5,340,000 tons (40,210,200 bbl.), an increase of nearly 13 per cent. over the production for the year ending in March, 1927. The production by years since the opening of the field in 1912 is given in the following table:

[1 ton = 7.53 bbl.]

Year Ended March	Tons	Year Ended March	Tons
1912 (7 months)	43,084	1920	1,354,631
1913	80,800	1921	1,767,070
1914	273,635	1922	2,310,098
1915	375,977	1923	2,913,908
1916	449,394	1924	3,583,000
1917	644,074	1925	4,221,000
1918	897,402	1926	4,470,000
1919	1,081,919	1927	4,735,000
		1928	5,340,000

The actual production represents only a small proportion of the potential production.

The Masjid-i-Suleiman Field

The present producing unit, the Masjid-I-Suleiman, is an anticline some 20 miles in length by 4 miles in width, including three domes as so far proved. The producing horizon is a very open, dolomitic limestone, which, while showing much variation in texture and porosity, is so connected that the lowering of pressure in one section of the field quickly affects the whole area.

The topography of the field is broken, with differences of well elevations of as much as 1100 ft. The depths to the limestone vary from about 800 to about 5000 ft. The closed-in pressure of the oil wells varies from zero to 50 lb. per sq. in. and that of the gas wells is about 450 lb. Although the static oil level may be several hundred feet below ground level, in oil wells of high elevation, all the wells flow continuously or intermittently after they are once started—the majority continuously. The gas is very high in hydrogen sulfide in gas-oil wells of low pressure.

* Chairman, Anglo-Persian Oil Co., Ltd.

In high-pressure wells, the hydrogen sulfide is more largely absorbed by the oil. At rock-pressure conditions the gas is dissolved in the oil, coming from it as the pressure is reduced. The oil and gas are separated in the field and the oil is transported to the refinery at Abadan Island at the head of the Persian Gulf, a distance of about 145 miles.

The high hydrogen sulfide content of the gas makes it very poisonous, and its use in a commercial way constitutes a problem of some proportions. The total absence of helium, and the presence of only traces of argon are matters of interest.

The wells vary in potential production from about 1000 to 20,000 bbl. per day with an average of about 8000. The oil is a mobile liquid, brown in color, with a green fluorescence. Its mean specific gravity is 0.837. It flows from the wells accompanied by scarcely a trace of water.

It is an oleosol in which small amounts of asphaltic compounds and amorphic waxes are dispersed in a hydrocarbon-continuous phase. The asphalts are readily flocculated by a trace of sulfuric acid, while the soft waxes are slowly deposited when the oil is allowed to stand undisturbed.

Other Producing Areas

During 1928, in addition to the further testing and development of the Masjid-i-Suleiman field, production was proved or developed in three additional areas.

About 55 miles S. S. W. of the Masjid-i-Suleiman field another promising flowing structure (Haft Kel) has been found and its testing is now going on to determine its extent. Arrangements are being made to produce from this field. The crude will gravitate to Kut Abdullah, one of the main pipe line booster stations, 50 miles distant, which is 67 miles from the refinery at Abadan.

Still further to the south, about 100 miles, flowing production has been proved. Further drilling will be necessary to prove the potentialities of this area, since the first well with 1125 lb. closed pressure is not in good shape for completion.

To the north in the Naft Khana field almost on the borders of Iraq, a large production has been proved and shut in. This field can not be produced except to a small extent for local refining until a pipe line outlet is constructed to the Mediterranean.

In Iraq, testing operations continued. The following statement was made by the Chairman of the Anglo-Persian Oil Co., Ltd., at the nineteenth ordinary general meeting of that company in November, 1928: "Recent drilling in Iraq has met with decided success but many of the wells are comparatively deep, gas pressures are high and rapid drilling is not easy. Much remains to be done before the path is cleared for final schemes of development, but the future is bright with promise."

Control of Production

The operating control of the Persian fields is vested entirely in the one company giving an opportunity for unit operation and its accompanying advantages in the control of production, and the development of the field from a strictly engineering standpoint. Not the least of these advantages is the possibility of estimating accurately the reserves of the field at a comparatively early stage in its development. In the address to which reference has been made the Chairman said: "As an outcome of the continuous application of scientific methods to the examination of our main producing area (Masjid-i-Suleiman), I am able to state that its structural complexities have been so successfully studied that full reliance can now be placed upon calculations as to the magnitude of the oil reserves."

DISCUSSION

V. R. Garfias,* New York, N. Y.—Regarding Persia and Iraq, there are two rather interesting things. In Persia, the history of production for the last five years has been "uniformity." I think it has fluctuated between close to 40,000,000 bbl. for this last year and about 32,000,000 for five years ago. It really is a unique example of what can be done with intelligently mapped big-scale unit development.

In Iraq, a peculiar situation exists; besides the English and American and Dutch interests, there are the French interests, whose chief concern is to meet the needs of the French nation from Iraq as soon as possible, so it is going to be a rather interesting problem to conciliate the claims of four different nations, with the French, in particular, very much interested in getting their share of the oil in a hurry.

N. E. Odell,† Cambridge, Mass.—Persia has the unique advantage of being under one management, and these principles have been applied, I suppose, in a way that has never been possible before. I refer to such controlled operation of an area as implies, in the words of Captain Comins, "a uniform and longsighted drilling and production policy that can be applied to the whole of a reservoir unit."

* Manager, Foreign Oil Dept., Henry L. Doherty & Co.

† Harvard University.

Petroleum Production in Dutch East Indies and Sarawak (West Borneo) in 1928

By J. Th. Erb,* The Hague, Netherlands

(New York Meeting, February, 1929)

Oil is found in commercial quantities in the islands of Sumatra, Java, Borneo, Tarakan and Ceram.

The oil deposits of the Dutch East Indies and Sarawak are with one exception of Tertiary origin and as a rule are bound to anticlinal structures. The number of layers varies in most fields and in some of them as much as 14 oil-producing levels have been established.

The crude oil varies rather much in composition. Some of it, particularly from North and South Sumatra, has a gasoline content up to 50 per cent. Borneo produces mainly wax oil, while the Tarakan oil can be used directly as liquid fuel. In Java both wax and wax-free oil are produced.

In all important fields installations have been erected to treat the wet gas. The lean gas is used for gas-lift purposes, Mariëtta process, and as fuel for boilers and motors, either in the fields or in the refineries.

Formerly only percussion systems (Canadian, Californian and a drilling system devised especially for the purposes of the Royal Dutch Petroleum Concern) were applied in the Dutch East Indies, but in recent years the rotary system has been predominant and good results have been obtained with it.

The deepest producer has recently been struck in South Sumatra at a depth of 1624 m. (5328 ft.), with a daily production of about 350 cu. m. crude oil.

The crude is brought by an extensive system of trunk lines to the refineries, of which one is in North Sumatra (Pangkalan Brandan), two are in South Sumatra near the town of Palembang, two in East Java (Tjepoe and Wonokromo), one in East Borneo (Balik Papan) and one in Sarawak (Miri).

Production

The principal producing concerns in the East Indies are: De Bataafsche Petroleum Maatschappij, the producing subsidiary of the Royal Dutch Petroleum Concern; Sarawak Oilfields Ltd., one of the

* Director, Royal Dutch Petroleum Co.

producing subsidiaries of the Anglo-Saxon Petroleum Co., Ltd., and Nederlandsche Koloniale Petroleum Maatschappij (Standard Oil Co. of New Jersey). The combined production of these companies in 1928 was:

	Metric Tons*
North Sumatra	157,501
South Sumatra	880,571
Java	469,773
Borneo (including Sarawak and Tarakan)	3,439,848
Total	4,947,693

* 1 metric ton = 7.36 bbl. on the average.

Russian Oil Fields, 1927 and 1928

By Basil B. Zavoico,* Tulsa, Okla.

(New York Meeting, February, 1929)

The production of all Russian fields increased from approximately 74,000,000 bbl. during 1926–27, to approximately 83,000,000 bbl. during 1927–28. Of this amount Baku was responsible for 54,500,000 bbl., Grozny for 25,800,000 bbl., and Emba for 1,200,000 bbl. Accordingly, the proportional importance of the Grozny oil field has been considerably increased, the present production being twice that of 1913.

The most notable factor of production during 1927–28 was the importance of gushers; 40.8 per cent. of the total was thus obtained. In the Baku fields 26 per cent. of the total, and in Grozny 74.2 per cent. of the total were produced by naturally flowing wells. This may be explained by the reduction in authorizations for drilling by the central authorities, and, accordingly, the local trusts increased the production to the planned figures at the expense of the proved prolific reserves. In Baku region, the Surakany oil field produced 36.1 per cent. of the total Baku production, or an equivalent of 53,800 bbl. per day, the largest percentage coming from the fifth horizon. Next year's plans call for continual development of that horizon as well as of the sixteenth horizon in the Bibi-Eibat field, which was opened lately. In the Grozny fields the New Area (Bellik) was responsible for 79.4 per cent. of the total production.

The authorized plan for 1928–29 production calls for 92,200,000 bbl., and a reasonably accurate estimate for 1932–33 production is placed at 156,000,000 bbl., with Baku contributing 101,800,000 bbl., Grozny 44,100,000 bbl., Emba 6,200,000 bbl., Kuban 2,100,000 bbl., Saghalien Island 1,400,000 bbl., and Russian Turkestan 400,000 bbl. In connection with recent discoveries in the Baku area these figures are quite conservative.

The average production per well per day in the Baku oil fields was 49.2 bbl., in Grozny 175 bbl.; in detail, Surakany oil field averaged 280 bbl., and the New Area in Grozny 514 bbl. per day. New completions in all Baku fields averaged 264 bbl. per day, and in Grozny 970 bbl. per day. These figures show a considerable progress in the technical development of all fields, compared even with the prerevolution figures, since all the improvements are noted in the fields that are over 30 years old.

* Consulting Geologist.

Modern drilling and more efficient methods of handling water horizons are largely responsible for the increase in the averages.

A total of 1,152,000 ft. was drilled during 1927–28, as compared with 1,220,000 ft. during the preceding year, indicating a small decrease in total footage. Drilling methods were further improved; 72.1 per cent. of the total footage was made by rotaries; 22.0 per cent. by cable tools; 2.1 per cent. by the Russian turbine method, and but 3.8 per cent. by the old percussion method. The figures of drilling, when compared with production, will further indicate that most of the drilling for production was made to the known prolific horizon held in reserve.

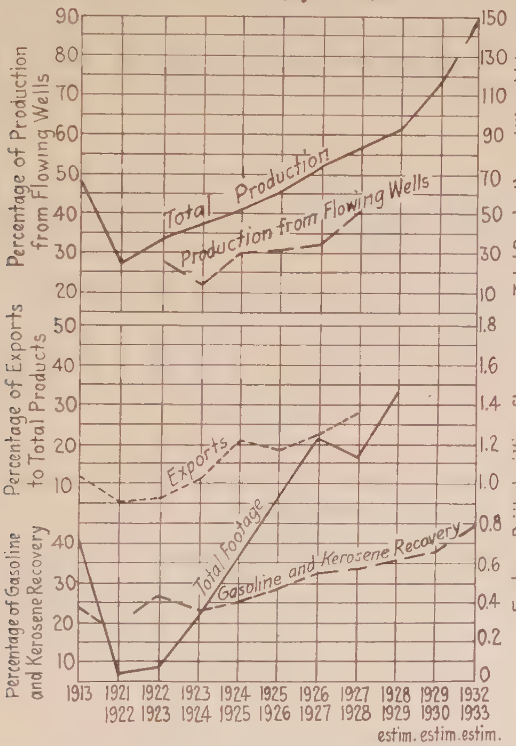

FIG. 1.—GRAPHICAL PRESENTATION OF MOST IMPORTANT PHASES OF SOVIET UNION OIL INDUSTRY.[1]

REFINED PRODUCTS

During 1927–28, 63,000,000 bbl. were run to refineries, this representing 80.5 per cent. of the total production and indicating a very considerable increase in the refining capacity of the Russian plants, since in the prec ding year, when all the refineries were forced to the limit, only 73.6 per cent. of that year's production was refined. The most interesting developments in the refining branch of the industry were in the light

[1] Years given in figure are operating years—1921–1922, 1922–1923, and so on.

products, thus, the production of gasoline from all of the refineries amounted to 7,190,000 bbl., and production of kerosene was 14,976,000 bbl. The recovery of gasoline and kerosene in Baku was 5.31 per cent. and 24.7 per cent., respectively, of the total runs, the slight decrease as compared with last year being due to the use of a larger amount of heavier Binagadi oils. In Grozny, gasoline recovery was 16.3 per cent., and kerosene recovery 16.63 per cent., of the total runs, thus indicating a slightly better recovery of lighter products than in Baku. Cracking operations are still in the experimental stage, the Vickers units in Baku running only about 1500 bbl. per day with 25 per cent. recovery of gasoline. At this time the Soviet management is ordering American cracking installations. By 1932, according to the 5-year program, there will be in Russia 65 cracking installations with a total output of 33,800,000 bbl. of gasoline.

Marketing

The improvement in marketing was considerable. A 14.3 per cent. increase was noted in the quantity of products marketed at home, while the exports increased 33.1 per cent. These figures indicate that the rate of the increase in marketing is greater than the rate of the increase shown by the producing and refining branches of the industry as a whole. Gasoline represented 27.9 per cent. of the exports, amounting to 6,770,000 bbl., while kerosene represented 24.3 per cent. of the exports, amounting to 5,240,000 bbl. In the home markets 9,380,000 bbl. of kerosene were sold, this representing 17.6 per cent. of the total consumption of petroleum products in Russia. On the other hand, the consumption of gasoline, while increasing greatly as compared with the preceding year, was but 826,000 bbl. during 1927–28, representing only 1.37 per cent. of the home consumption of petroleum products, and 11 per cent. of the total Russian gasoline output. In the future the same relationships will exist, since the development of motor transportation in Russia on a large scale is far away, and the Soviet authorities have to market the largest portion of the gasoline production outside of the country.

In March, 1929, the Soviet Oil Syndicate signed an agreement with English distributors, ceasing competition. Compromises on both sides were effected. Accordingly, the prices were immediately raised 4½ c. per gal. by the English dealers and 5 c. per gal. by the Russian marketing unit (a total appreciation per year of $35,000,000). An interesting fact is that the prices were depressed so much by a relatively very small proportion of total British gasoline requirements. Thus, out of 20,000,000 bbl. of gasoline consumed in the British Isles, only 8 per cent. was contributed by Russia. The effect of the agreement should be far-reaching in stabilizing the oil industry of England and Russia, and should help American importing companies.

Pipe Lines

The construction of pipe lines and refineries in the areas of large consumption is now seriously debated in Russian oil circles. The latest completion is the Grozny-Touapse pipe line (325 miles), having a capacity of 7,500,000 bbl. per year and constructed at a cost of $14,000,-000. A pipe line is now being built from Baku to Batum (500 miles) in addition to one now pumping kerosene. Large refineries under construction at the terminals of Batum and Touapse, on the Black Sea, will specialize in export requirements. Both refineries are also to serve the southwestern portion of Russia through the port of Odessa. The largest project so far provides for a 12-in. pipe line from the Caspian Sea to Moscow (roughly 1000 miles) and the construction of refineries in Moscow, thus serving the greatest industrial area of Russia from its own refineries. Also, a third pipe line is being planned from Baku to Batum in connection with the contemplated increase in export trade. From Emba fields a line is projected to Samara on the Volga River (400 miles) to take care of increasing production in that area. The pipe line to Moscow should be of the greatest benefit to the Russian oil industry since it would greatly stimulate the home consumption of petroleum products, while its estimated cost, $50,000,000, could be quickly returned from the difference in cost by railroad and but seasonal transport over the Volga River.

Labor

No improvement in the labor situation was observed if we are to compare Russian with American labor. A 7-hr. working day is being actively introduced in the whole industry, which means that the great army of workers in the oil fields will be increased instead of decreased; however, the long-time outlook is considerably better as production is expected to double by 1932 33, as against an expected increase of only 7 per cent. in labor.

New Development

Among the discoveries of the past year, only two can be classed as major, and both are, in reality, extensions of the old fields. In the Bibi-Eibat field proper a deeper horizon, the sixteenth, was uncovered, the discovery well producing 3200 bbl. per day from 3470 ft. This development is of extreme importance, since the flowing wells in the old Bibi-Eibat are now rare, and the Azneft needs all the reserves it can get, wildcat areas on the Apsheron Peninsula having proved so far, to be eminently disappointing.

The Bibi-Eibat-Bay extension will undoubtedly also include production in the sixteenth horizon. The factor of unit operation will go far to make this horizon one of the most important reserves for the Azneft.

The most interesting factor is that the average production per acre in Bibi-Eibat field over an area of 400 acres is already more than 800,000 bbl., and several parcels produced as much as 2,500,000 bbl. per acre. The deeper sands are evidently in line with the upper ones, and the per acre recovery may very well be doubled or trebled in the years to come.

The Surakany field was considerably extended to the south by the opening of the Kara-Choukour sector, which is claimed to be a separate field, but, in reality, is an extension of the producing arch north of the city of Baku proper. The first discovery well indicates that the Surakany field may cover as large an area as Balakany-Ramani Old Area.

Kala district, east of the producing fields of Apsheron Peninsula, proved to be a complete failure, half a dozen tests drilled there not encountering commercial production. This area had been regarded very highly by geologists and oil producers, because of favorable structural conditions and numerous seepages of oil and gas; but the subsurface proved to be extremely faulted and broken up, which is not favorable for commercial accumulation.

The Puta district, south of Baku, is apparently a highly broken up area, and at the best will contribute small pools. South of Apsheron Peninsula, in the Saliani area, no commercial production has yet been obtained because of the lack of transportation facilities, but it is planned to begin experimental exploitation during 1928 29. Production of approximately 300,000 bbl. is anticipated during that year.

On Saghalien Island, in the Pacific Ocean, the Saghalien Trust completed its first well, which is estimated for 150 bbl. per day. Japan has a checkerboard concession on the island, which is now in operation, therefore the Soviets were forced to drill the offsets to the producing wells of the Japanese concessions.

Production Policy

Conservation policies are of no importance to the Soviet Union, because the technical development of the country does not permit rapid development of new fields or the rapid construction of pipe lines. If we consider that the Grozny-Touapse pipe line took approximately three years to build, it will be at once evident that the foreign markets have really nothing to fear from the Russian oil fields in the way of spectacular increases in the exports. This would indicate clearly that no production is being held back, but that the development of the richest horizons, such as the fifth in Surakany, sixteenth in Bibi-Eibat, and the New Grozny oil field is being delayed in accordance with the general policies of the Central Industrial Committee for holding a very considerable proportion of the proved prolific production in reserve and developing less prolific units to the limit of the transportation facilities.

Chapter V. Petroleum Economics *

The Crude Oil Supply

By Howard S. Bryant,† Tulsa, Okla.

(New York Meeting, February, 1929)

The year 1928 has recently passed from the picture and it is at this time that the various divisions of the oil industry are giving thought to plans for the present year.

The outstanding characteristic of the industry in 1928 was the successful curtailment of oil production to the market's needs.

It has been thought advisable to look ahead and endeavor to anticipate the oil demand for the coming year, and thus determine the volume of oil that can be safely produced without causing major additions to surface stocks.

The year has been one of smaller additions to stocks than in 1927, a record demand for oil products, and a further developed spirit of cooperation among oil producers, as well as various other achievements. It is well to pause and take stock of ourselves.

Present Status of Crude Oil Supply and Demand

The total daily new supply of oil is at this time[1] about 2,960,000 bbl. per day, made up of 2,585,000 bbl. domestic crude production, 125,000 bbl. casinghead gasoline, and 250,000 bbl. of imports.

With the present low consumption, due to the falling off in the winter season demand, it is estimated that about 150,000 bbl. a day are now being run to storage, and that the first three months in 1929 will see large-sized additions to storage.

Consumption plus exports of oil have increased at a regular rate from year to year, and although oil production in 1928 passed the 1,000,000,000 bbl. mark for the second time in the history of the United States, with a production of 25,000,000 bbl. more than in 1927, only 30,000,000 bbl. were added to storage during 1928. This is compared to an addition of 65,500,000 bbl. in 1927.

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* A paper by James A. Veasey, entitled "May the American Petroleum Industry through Voluntary Action Meet Its Problem of Overproduction?", was presented at the Production Control Session, Annual Meeting, A. I. M. E., Feb. 18, 1929; for this paper see *Mining and Metallurgy* (1929) **10,** 190.

† Skelly Oil Co.

[1] Jan. 1, 1928.

Although there was an overproduction of oil in 1928, this overproduction was less than half the amount added to storage in 1927. The grand total of all stocks is at this time 610,000,000 barrels.

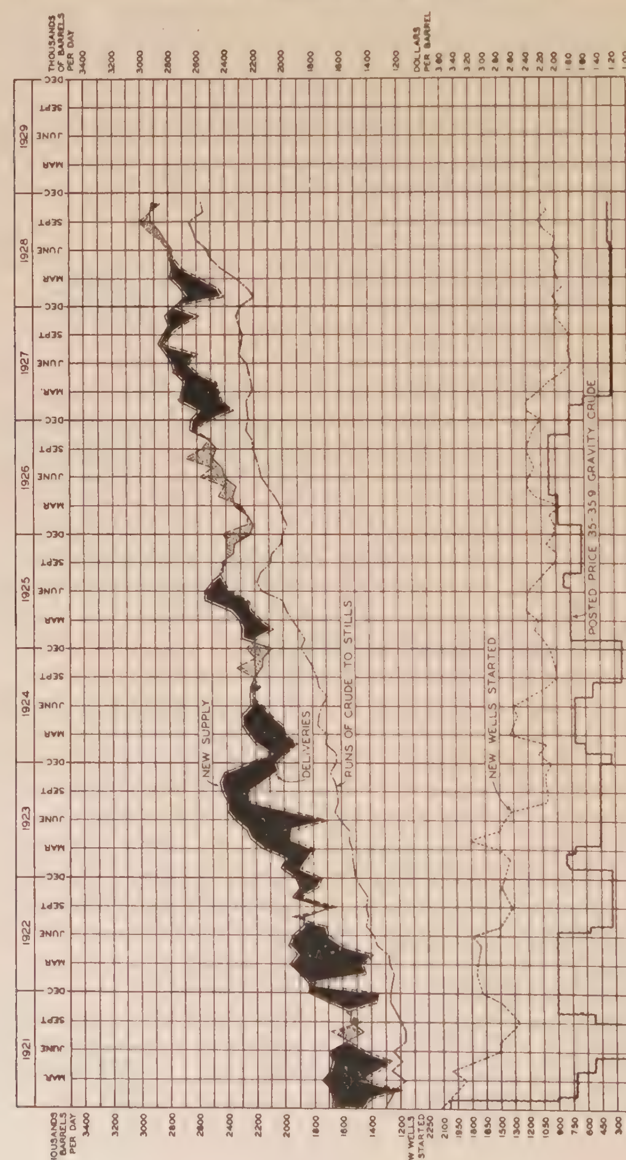

FIG. 1.—TREND OF THE PETROLEUM SITUATION IN THE UNITED STATES.

Oil production in 1928 had a much lower percentage increase over the previous year than did oil production in 1927, showing only a 2.5 per cent. increase as against 17 per cent. for 1927. Oil consumption in 1928 increased 5.8 per cent. over the previous year, as against a 4.1 per cent. increase in 1927, a substantial gain in consumption. Statistics

are taken from the monthly petroleum report of the U. S. Bureau of Mines, with figures for the last month in 1928 estimated.

Fig. 1 shows the relation of oil supply to demand and the resultant effect on storage, and the relation of the whole to average oil prices. It will be noted that a good measure of stabilization has been attained in oil prices and in the number of new wells started each month since early in 1927, and that there is a gradual increase in the number of new wells started.

In the last half of 1928 stocks of crude oil were drawn upon, but the first half had such a substantial oversupply, or stated better, underconsumption, that the average for the year showed a 30,000,000-bbl. gain in total stocks. The effect of seasonal variation in demand is well illustrated here, when demand increased faster than supply after January, 1928, and exceeded supply for that summer. Supply was increasing, however, at a fairly regular rate; such changes in stocks as took place might be regarded as over or underconsumption with respect to the oil supply.

From January to August, each year, oil deliveries increase at a regular and rapid rate, and it will be noticed that the curves representing deliveries in those months are about parallel to each other. This facilitates the fairly accurate estimation of a coming year's demand, and indicates normal consumption by quarters of months.

A very important factor entering in the crude oil situation in 1927, and becoming a major factor in 1928 is that of shut-in oil reserves. The bulk of such shut-in reserves are in West Texas, California and Wyoming, and although most of this amount is measured by 1-hr. gages at the wells and this practice is not considered reliable in giving a true picture of what these wells would do if produced over a longer period of time, and although transportation and storage facilities have not been developed to handle such reserves, a large amount of crude oil is shown to be easily available. This amount is in size far beyond the capacity of the present oil market.

It will be observed, then, that when there are large ready oil reserves, the oil market will regulate the supply to be drawn upon, and under such conditions only such an amount will be produced as will be needed.

The rule that the oil demand regulates the oil supply is operative similarly in times of closer balance or in times of overconsumption just as well, taking into consideration movements of oil prices. The effect is harder to see, however, due to the premature discounting of a favorable oil market in the usual form of an oil price rise ahead of time, and also the reverse price lowering with a lag. This is in no small part due to the eagerness of many oil production men to see the return of better conditions before they are justified, and to their tendency to ignore any impending bad conditions until the latter event actually occurs.

The relation of the oil supply to the oil demand, which governs it, can be seen by a study of these two factors for any one time. With an understanding of the underlying conditions the oil man is afforded a perspective that enables him to look ahead for a short period of time. It will be seen that most of the elements in the relation can be expressed numerically and graphically. The human equation cannot be measured by these methods but must be considered as equally important and subjected to just as close scrutiny to understand such factors as cooperative production ventures, shut-in agreements, various forms of conservation projects, and the psychology attached to any impending change in oil prices.

Brief History of Mid-Continent and California Oil Fields

The 12 months of 1928 ended with the highest daily production for the year at the end of the year, the three states, Oklahoma, Texas and California each producing about 720,000 bbl. a day. This record production has been attained only once before, at the end of July, 1927, when the Seminole area reached its peak.

The Seminole area continued to dominate the situation in Oklahoma throughout 1928. The present moment finds large proved areas at Maud, Mission, St. Louis and probably Allen, which had drilling restrictions operative most of last year, and are being drilled.

Geologic knowledge of 1927 has been supplemented by an abundance of data from wells drilled throughout last year, resulting in the extension of the Seminole development outward from the known pools into new areas. At present the entire Seminole district, including St. Louis, is producing 420,000 bbl. a day, as against 360,000 bbl. a day one year ago.

The most important new strike in Oklahoma of the year is the Indian Territory Illuminating Oil Co.'s new 5700-bbl. well located 1 mile southeast of Oklahoma City. The well is located near the center of a large block of acreage and is producing from a deep pay encountered at from 6376 to 6500 ft. Although there are 27 new wells located around the producer and there is much diversified small acreage in the block, development will be slow due to the great drilling depth. Additional production is not expected until the middle of the year.

Discovery of an apparently important and heretofore unknown structural trend in Sedgwick County, Kansas, was made in the summer of 1928. Six wells have been drilled to date, showing two or possibly three new pools. The wells produce from the Ordovician dolomite, and also what is probably the Chat formation, and have an initial production of from 800 to 4000 bbl. each, at depths from 3000 to 3400 ft. It is the present opinion of certain geologists that this new production may be on another granite ridge subsidiary to and somewhat paralleling the main granite ridge of Kansas. An extensive leasing and drilling campaign is

well under way in the area, with 40 wildcat wells located and drilling. Although the present known production will probably be slowly developed, other new pools are expected to be located and these may be brought under development in the middle of 1929.

Several wildcat wells in the Western Kansas area are showing favorably and with the greatly increased number of wildcat wells located, and the number of drilling blocks being assembled there, this area may show new and important production in the coming year.

The Yates and Hendricks pools and the Howard County area of West Texas, are the controlling factors in the production of oil in Texas. In each area the amount of oil being produced is but a fraction of the potential production, and is based on the pipe line outlet. The production per lease is prorated in accordance with the amount of proved acreage and the potential production of the lease against the others, or both. The total potential production of the three pools, on 1-hr. lease gages, is reported as about 7,050,000 bbl. a day, while the daily production therefrom is but 285,000 bbl. a day. This is reported to be all the allowable capacity for these areas in the present pipe lines, railroad facilities, and local refineries.

At the end of 1928 all West Texas was producing 350,000 bbl. a day, just 100,000 bbl. a day more than the production at the beginning of that year. It is expected that the transportation facilities from this area will be slowly enlarged during 1929, probably to the extent of between 100,000 and 200,000 bbl. a day.

Shutting in of large oil reserves with proration to an allowed amount has been successfully practiced here on a scale never before attempted. Erection of high-costing tankage and long-distance pipe lines has been to an extent avoided, and the low-gravity sulfur oil has been held back from a market already burdened with too much crude supply. It is pointed out that this district has done all if not more than its share in holding back the new oil supply to the demands of the market, and that other high-production areas should bear their proportional share of such burdens.

California has seen much new oil development planned for 1929. Long Beach is holding near its peak and promises to do so for some time to come. Santa Fe Springs is expected to reach its peak production in the spring or summer of the year, when the 200 wells now drilling and deepening will raise the present deep production of 110,000 bbl. to an estimated 200,000 to 250,000 bbl. a day, from the Nordstrom, Buckbee or lower pays.

Elwood Terrace, discovered in 1928, near Santa Barbara, now has four producers averaging about 4000 bbl. each, owned entirely by the Barnsdall Oil Co., and the Rio Grande Oil Co. development is expected to be on a very conservative scale, but drilling sufficient to test the struc-

ture is expected to get under way early in the year. It is estimated that about 30,000 to 40,000 bbl. a day flush will be developed next year.

Kettleman Hills, Lawndale and Hyde Park, each with one or two producers, will see further testing in 1929, and unless shallower pays are discovered these pools will probably take no important part in the production schedule until about the end of 1929.

Midway Sunset and Inglewood, although offering deeper zone probabilities, fit into the background of this production picture, because of the amount of oil already in sight in the above fields.

The production curve for California should show an upward swing from now through the summer of 1929, unless a substantial amount of the expected flush oil is shut in under agreement. California operators entered the year 1928 with about 70,000 bbl. a day of shut-in production, which was increased to 120,000 bbl. in the summer, while at the present writing it is estimated there are 100,000 bbl. of oil voluntarily shut in.

Importance of Growing Demand

Consumption plus exports of all products has increased at a rather regular rate from year to year, during the past. Estimates of average daily consumption for 1928 were made early in that year and appear to be substantiated by a consumption so far of about 2,770,000 bbl. a day over the year. A careful estimate of consumption involving a study of trends for all products indicates an average daily consumption of 2,745,000 bbl. for the last 3 months in 1928, and the first 3 months in 1929. Average daily consumption plus exports over all 1929, assuming a normal rate of increase, to which there has been no appreciable exception in several past years, will approximate 2,945,000 bbl. a day, an increase of about 200,000 bbl. a day over the average of 1928.

The normal decline of old settled fields is an important part of the picture. This decline is generally estimated at 20,000 bbl. a day monthly, and we may therefore expect a normal yearly decline of about 250,000 bbl. per day in settled production.

Considering the country as a whole, from 35 to 50 per cent. of the total production at any one time can be considered as flush production, which has a relatively rapid decline. The average for the past 5 years has been close to 40 per cent. flush. The amount which flush production declines in any one year cannot be directly applied to another year, due to the differences in the way wells of one area decline as compared to those in another.

Taking into account a yearly increase in consumption of 200,000 bbl. a day, and a yearly decline in the older settled fields of the United States of some 250,000 bbl. a day, it is necessary to produce, during a normal year, some 450,000 bbl. a day of new oil supplies to keep up with consumption. Due to the additional great decline of the present flush

production, it may be necessary during the next year to bring to the market a total of between 600,000 and 700,000 bbl. daily of new oil, in order to balance demand.

To supply this 600,000 to 700,000 bbl. daily, we have at present in sight an increase of 100,000 to 200,000 bbl. a day from the shut-in wells in West Texas, when the additional transportation facilities now planned will permit; a probable increase in the Mission, Maud, St. Louis and Allen areas of Seminole of 150,000 to 200,000 bbl. a day; 150,000 to 200,000 bbl. from Sante Fe Springs and Elwood Terrace in California, and a potential import of another like amount of oil from Venezuela, aside from new oil fields recently proved in southeastern New Mexico, at Oklahoma City, Okla., and in Sedgwick County, Kansas. In summation, there appears to be a supply of oil already in sight sufficient to supply the country's needs during the next year.

Viewing the situation at the present time, supply and demand seem to be in such relation as not to warrant the stimulus of even a moderate rise in the price of crude oil until after the first half of the year, or likely not until the season of high consumption, next fall.

A moderate price rise in the summer or fall will be expected to precipitate a widespread wildcat drilling campaign in Oklahoma and Kansas, where the number of new wells has been held down to lowest levels since early in 1927. The effect in West Texas would be to cause the probable release of an additional amount of shut-in production, and to stimulate the building of more pipe lines and storage facilities in that district.

Importance of Shut-in Crude Oil Reserves

In November, 1927, Joseph E. Pogue stated that he felt that the oil industry would continue to go through a period of strain for an indefinite time in the future. This it has done since early in the year 1927, down until the present, a duration of 2 years. The present statistical position of the industry—meaning the relation of immediately available oil to our fairly definitely known demand—is farther from a balance than at any time during the past 2 years, commonly referred to as "bad years" in the industry.

The amount of potential oil supply in the form of shut-in reserves has mounted rapidly, and as drilling defines new production in amounts beyond the demand of consumption and exports, the shut-in reserves will receive additional potential volume.

The writer feels that that hypothesis postulated a year ago wherein it was tentatively believed that the industry was entering a new economic era, has been at least partly proved. The oil industry is enjoying the longest period of stabilized prices in its history, and for an average of 1 year production has been held to within 80,000 bbl. a day of consump-

tion, with a potential production conservatively estimated at twice the total amount actually produced.

The economic goal of any industry is to develop to that position where prices of its products are stabilized. It is believed that the crude oil-producing industry has made fair progress in this direction. Although fluctuations in the price of crude will be observed from time to time, they are expected to be relatively small changes, unlike the ones occurring in 1921. The large shut-in oil reserve will prevent price fluctuations of a major degree.

Future Oil Supply

Each year, at present, must see the development of from 500,000 to 700,000 bbl. of new supply to fulfill the increasing demand and replace the decline of flush and settled production in that year. The late sentiment that our often-estimated underground reserves were about to give out has now been replaced by the feeling that when the drills get busy there will always be sufficient oil to supply the demand. The latter hypothesis has never thus far been disproved. However, the geological sciences are developing at a rapid pace and the rate of discovery of oil pools has also increased rapidly. It is probable that at a time in the future practically all the petroliferous provinces will be defined in area and tested to at least moderate depths. The outlook then will depend on the economic or physical depth possible to drill, the more intensive development of the known shallower pools, and oil substitutes.

In connection with the development of new oil supply it is necessary to present the role played by the petroleum geologist. Detailed surface geology still plays a very important part in the finding of new oil pools, although practically given up by many as an important method several years ago. There are yet fairly large unexplored areas in the United States where early prejudices or insufficient data have caused lack of exploration; in addition, it has been found that in the light of later facts a large proportion of the early surface detail work now bears checking over.

The subsurface geologist contributes many facts helpful in both locating new pools and developing proved oil pools, from the studies of the formation records of wells drilled in the past. Although this branch of geology is comparatively young, there already has been developed highly organized systems for the preservation and use of records of wells drilled throughout all oil-producing areas.

The regional geologist uses the tools of both the surface and subsurface students, and endeavors to see the broad regional aspects of sedimentation and structure, keeping in mind at the same time evidence contributed by surface and subsurface facts. His work is to look far ahead of present development and production, and foresee new oil provinces.

That there is enough room and plenty of possibilities for the discovery of oil fields in the known petroleum provinces for several years to come seems a fair assumption. The major geologic feature in the Mid-Continent area, the Kansas, Oklahoma and Texas salt basin, will see extended exploration in West Texas and into the southeast corner of New Mexico, in central and western Oklahoma and in central and western Kansas. In California much exploration is expected in both the Los Angeles basin and the San Joaquin Valley basin where new pools have been recently opened.

Results of 1928 and the Present Situation

More definite realization of the great need of getting together to solve the problems of stabilizing oil production and oil prices means the passing of one distinct milestone along the path of progress of the industry.

Men engaged in the oil industry's various branches are getting together more often than ever before, and the road is being paved for still further cooperation and organization, benefits from which promise to be certain to all engaged in the industry. These get-togethers and their results contribute materially to the oil industry's good will, and greater cooperation with the public is gained thereby.

Concerning the immediate situation it can be stated that the tendency has been to discount too readily the millions of barrels of shut-in reserves in the Hendricks and Yates areas in West Texas. It appears fair and equitable that more of the major oil-producing areas prorate production, each bearing its proportional burden, rather than that two or three areas bear the entire burden.

Posted prices for oil have remained steady for nearly 2 years, and at a figure believed to be much above what they would have declined to, had not the large shut-in reserves been set up, or had flush production been allowed to mount to its peak, as has been the usual history in an era of overproduction. New drilling has been held to a minimum, with wildcatting noticeably restricted. A tendency toward stabilization can be observed all along the line, in producing, refining and marketing divisions, and the industry has escaped, at least for a time, that alternating condition of "feast or famine" which it had come to regard as its own peculiar and chronic affliction.

When the posted prices for crude oil first reached their low levels in early 1927, considerable time was spent in well-informed circles calculating the speed with which most oil-producing companies were approaching bankruptcy. Activity was at a low ebb, with only 750 new wells drilling, the fewest new wells per month in over 10 years.

At the present time, with the poorest consumption season at hand, the number of new wells has increased to 1050—the average of the number of new wells in the prosperous years of 1925 and 1926, and there

has been no significant rise in average oil prices since those very low levels of 1927.

Instead of being involved in the promised bankruptcy the average oil company is now able to make a profit, and many are even undergoing programs of mild expansion, shown by the recent increase in the number of new wells drilling.

In review, the whole economic balance of the industry today is founded and dependent upon cooperative limitation of oil production; the patient has had a phenomenal recovery, and tends to forget how ill he was, and although his strength is returning fast, he had best take precautions to prevent a relapse—an event of very serious consequence in his present weakened condition.

The present minute finds oil production at its highest all-time peak, with further increases promised, new drilling activity at the highest point in the last 2 years, consumption at the lowest season, and substantial addition to stocks scheduled for the first half of 1929, unless this additional substantial production is shut in.

All in all, the year 1929 as a whole, is looked forward to with confidence because a majority of the leaders in the industry are in favor of balancing supply with demand.

The Oil Demand, Supply and Price in 1928

By Campbell Osborn,* Tulsa, Okla.

(Tulsa Meeting, October, 1928)

From the viewpoint of practical economic engineering the main value in studies of demand and supply lies in the information they give concerning the next movement of price. The title of this discussion is too comprehensive for detailed analysis and it will, therefore, be narrowed to the question of price measurement.

The oil operator is interested primarily in net profits. Prices, costs and production determine them. Production is here used in its broadest sense. It includes refining and marketing. It is an operating problem. Prices and costs are economic considerations. Though costs are an important element of prices and profits, the subject is too large to be treated in a brief paper of this sort. In the long run, costs govern prices, but for the purpose of gaging prices in the immediate future the relationship of current demand and supply are more significant.

Operating, expansion, retrenchment, sales and storage policies of oil companies are largely influenced by the feeling of executives concerning this relationship. The stockholders of companies whose executives are wrong may suffer. Investors who err in their judgment may likewise lose. On the other hand, oil companies and investors who appraise these factors correctly and move accordingly will profit. It is an important subject worthy of careful consideration.

The author has been asked to discuss the subject for 1928. From the beginning of the year until the first of June, as illustrated by Fig. 1, oversupply prevailed in the face of restricted production, but from June to September, with record consumption, demand slightly exceeded supply and oil came out of storage in the United States as a whole. One of the main problems of the oil man is to decide whether this condition will continue and what the next movement of prices will be. Before he can do so he must have an understanding of the underlying conditions and of the facts that led to the present situation. With these facts in mind he is in a position to measure the effect of the present relationship of demand and supply on price and is afforded a perspective that may enable him to look ahead for a short period of time. The practical

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engineer, trained in economics and experienced in the use of data on the oil demand, supply and price, should be helpful to the oil man in studies of this kind. Valuable current data on these subjects are available to the industry and systematic use of it should be made in this way.

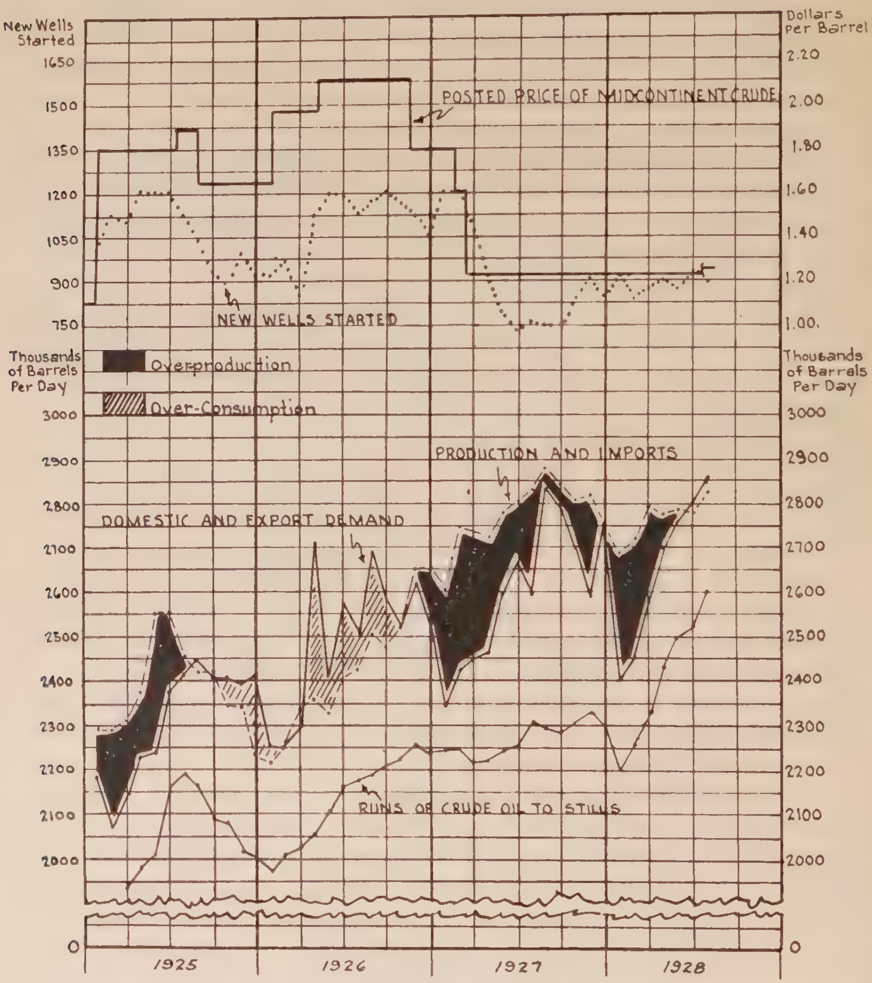

FIG. 1.—TREND OF THE PETROLEUM SITUATION IN THE UNITED STATES BY MONTHS FROM 1925 TO 1928.

The meaning of "oil economics" is not clear in the minds of many people at the present time. Some men think of it as dry, uninteresting tables of figures. When others hear of "economics" they think of the theory of government, the tariff, or taxation. Relatively few men recognize the industrial economist as a practical engineer or trained

business man skilled in his kind of work as much as the lawyer and the accountant are in their professions.

The economist uses figures and curves, requiring a mind trained somewhat in mathematics. They are merely working tools. The higher branches of mathematics are not necessary. If used sensibly they are helpful. A knowledge of the history of the industry is his main background. He studies conditions and trends and, knowing under certain circumstances what has happened in the past, makes allowance for new situations and arrives at conclusions regarding the results toward which existing conditions are leading.

The Underlying Situation

As illustrated by Fig. 2, from January, 1918, to July, 1920, demand and supply were fairly well balanced. There was overconsumption in some months and stocks were slightly lowered. Average prices[1] increased from $2.00 to $3.50 per bbl. Many did not seem to know then, and may not fully realize now, that supply is largely the result of price and drilling. Given high prices and stimulated drilling, production mounts. The actual movement of these factors shown in Figs. 1 and 2 confirm this statement. The rising curve of production since 1920, obtained from fewer wells than were drilled in immediately preceding years, should not be misinterpreted. It is the result of the high prices of previous years translated into improved methods of finding and production. The reverse rule is equally true. This principle will govern until unmined oil can no longer be readily discovered and no one can tell when this time will come. There certainly appears to be no danger of it for many years.

As a result of the strong prices in the years just prior to 1921, new drilling increased from 1234 wells in the spring of 1918, to over 3000 in the middle of 1920. The science of oil finding was greatly stimulated. Chronic oil shortage was the talk of the time. The price and the drill were not weighed. Supply mounted and the average price in a few months was lowered to $1.00 per barrel.

The author hopes he will not be misinterpreted. He does not mean to say "I told you so." Any other oil man writing or talking at this time would say the same thing.

The extent to which finding was stimulated is illustrated by some valuable figures recently compiled by C. B. Mapes, petroleum engineer of the Mid-Continent Oil and Gas Association. According to his figures only 13 major pools having a peak production in excess of 100,000 bbl. per day were developed by the industry prior to 1923. Since January of that year, 17, or four more than during the entire preceding history of oil,

[1] For 33° to 34.9° A. P. I. oil at wells in Oklahoma.

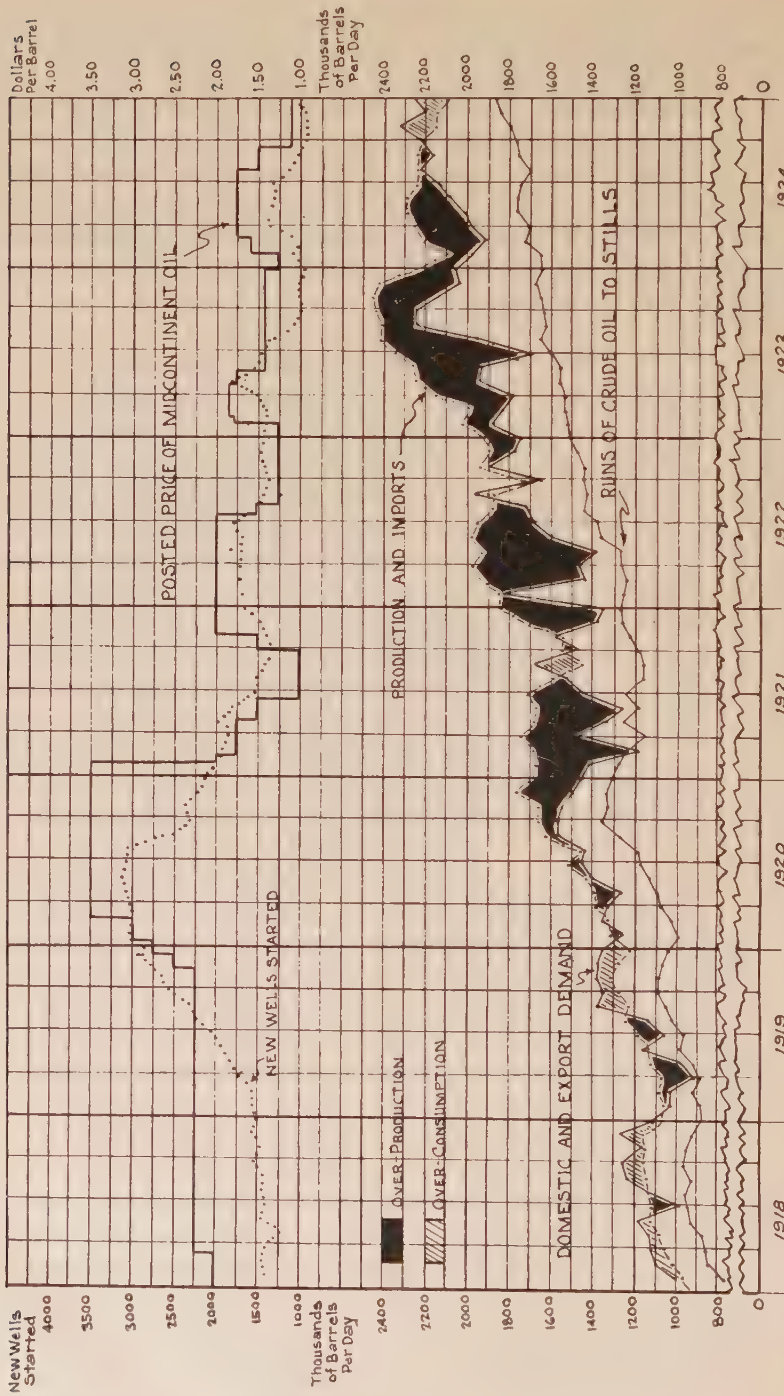

FIG 2.—TREND OF THE PETROLEUM SITUATION IN THE UNITED STATES BY MONTHS FROM 1918 TO 1924.

have been developed, and the operators are not drilling as many wells now as they did in 1918. From 1901 to 1923, an average of one major pool was developed every two years. During the past five years the average has been 3½ such pools per year.

The net result of this is well known. The price of oil in 1921 was below the cost of producing a large part of the current supply and many producers were driven to the wall or into bankruptcy.

It is noteworthy that during the period of high prices the volume of low-grade crude oil used for fuel was small. The area between total demand and runs to stills in Figs. 1 and 2 illustrate it.

With the exception of a few months when prices and new drilling were at low points, oversupply characterized the situation from 1921 to 1926. Stocks increased nearly 150 per cent. and average prices varied between $1.00 and $2.00 per bbl. Large quantities of crude oil were consumed as fuel. This is an important factor in the oil situation. Much crude oil is ordinarily taken off the market in this way when prices are low.

As shown by the drilling curve on the charts, less new wells than were drilled during immediately preceding years produced almost constantly increasing quantities of oil. The proof that this affords of improved methods of finding and producing oil—more intensive geologic studies, the use of geophysical instruments, the air-gas lift, etc.—is perhaps the most striking feature in the oil situation during the past decade.

At the close of 1925 and early in the year 1926 there was a lull in the development of new major fields. Despite good prices and new drilling at the rate of 1200 wells per month, overconsumption prevailed. The high drilling rate and $2.00 oil, however, soon began to make themselves felt. Production rose rapidly from the middle of 1927. During that year the large, well-known, prolific areas of the Seminole district in Oklahoma and of West Central Texas were developed. Heavy overproduction came on and the price was lowered to about $1.25 per bbl., a figure below the cost of producing from numerous settled and semisettled wells that yield a large proportion of the national supply. Climbing production promised to further lower the price and completely demoralize the producers. Something had to be done. Concerted attempts to restrict drilling and curtail production by mixed voluntary agreement, State regulation and sympathetic aid of the Federal Government were made. A large degree of success attended these efforts and an immense reserve of unmined oil was proved by the drill. Estimates of engineers as to the extent of this potential production vary from several hundred thousand barrels per day to more than the present total actual production. Some say that there is enough oil in sight in the counties of West Texas alone to supply consumers for several years.

As usual in the spring the demand for oil rose rapidly early in 1928. Reference has previously been made to the fact that by midsummer of

1928 it had overtaken retarded supply. In consequence surface stocks did not increase between June and September.

Basic Factors and Reactions

The facts illustrated in Figs. 1 and 2 justify close study. They afford a broad review of the natural laws that control price and, with methods of extending the demand and supply curves for a short period into the future, that will be referred to later, give the basis for price extension.

During the past decade the scope and detail of the current data on the oil situation have been greatly increased. The statistics are involved and care must be exercised so as to use the most valuable information. No single factor or limited combination of several features without due consideration of the broad, general picture can afford the basis for sound conclusions. "Liars" may figure, but figures do not "lie" if carefully selected and used as working tools. They are an element of the problem and their main value lies in the light they throw upon the broad rules that should be applied in conjunction with modifying data to measure prices.

The following suggestions of pertinent factors and principles may be helpful. Some of them were published by the author in a recent number of *Oil Field Engineering*.

Prices.—As well known by oil men and engineers, there are many grades of crude oil and refined products, and numerous prices. Probably the basic and most significant price is that paid at wells in the Mid-Continent for crude oil having a gravity range of from 33° to 34.9° A. P. I. The movement of this price is a good index to general oil conditions. Current prices are quoted by the oil trade journals.

Demand.—The dominant influence in the economics of the oil situation is believed to be the combined demand for all of the products of petroleum by consumers. It is the horse that pulls the cart. In the past the crude oil producers at times have tried to "put the cart before the horse." The nearest approach to actual demand that can be realized in the data available is the volume of products delivered by refineries for consumption. The U. S. Bureau of Mines publishes monthly information on this subject and comparable data on supply.

Current and Accumulated Supply.—It is felt that the most important relationship in the economics of oil is that which new supply bears to demand. The best available data on new supply consist of current crude oil and natural-gas-gasoline production, and imports of crude and refined oils.

Considered alone, stocks are, of course, the result of the relationship between past new supply and demand, and though of less significance than these factors, are important and should be carefully studied. The

most significant figures are those showing total stocks of oil, including refined products.

Fig. 3 illustrates the expansion of storage oil between 1918 and 1928. Stocks have grown each year except in 1926. At the close of 1918 they amounted to less than 200,000,000 bbl., but by the middle of 1928 amounted to over 600,000,000 bbl. Much of this oil can not be removed from storage at low prices without loss. It seems that prices high enough to liquidate it at a profit may bring on overproduction at any time.

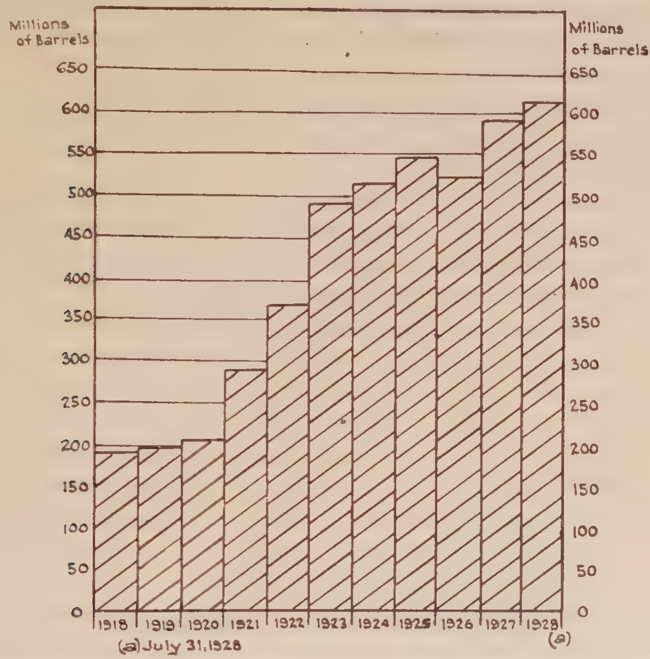

Fig. 3.—Stocks of crude and refined oil in the United States at the end of each year from 1918 to 1928.

The Law of Demand and Supply.—It is believed that the principal force at work in the oil situation is the law of demand and supply. This law is a more or less intangible rule. Its influence is felt in all competitive industries. It is always in control, but on account of the human equation and temporary modifying conditions, its effect during much of the time is difficult to trace. According to this law a persistent, substantial excess of supply over demand lowers the price of a commodity freely offered for sale. On the other hand, overconsumption inevitably increases the price. If this law is not recognized and prices handled in accordance with it, competition intervenes and the situation created by bad business judgment is corrected. The consumer is thus protected. At times he buys at prices substantially below costs and at others above them.

The economic principle underlying this law is axiomatic. If the quantity of any commodity freely offered for sale is greater than the buyers' wants, the sellers will reduce their prices in order to move their goods, but if the supply is less than the quantity desired by buyers, the sellers will withhold their goods from the market and permit buyers to engage in competitive bidding. The purchasers who need the goods the most offer the higher figure and thus the price level mounts.

Demand and supply necessarily vary, and consequently the curve of price is upward and in excess of cost at times and downward below cost at other times, reflecting whether conditions are favorable for buyers or sellers.

Sometimes the law of demand and supply seems to be held in abeyance, but the longer a sound price change is postponed the more inevitable it becomes and drastic it will be.

Stated in terms of the oil industry this law may be thus summarized: Mounting prices stimulate leasing and drilling, increase production and reduce consumption; falling prices retard leasing and drilling, ultimately reduce production and stimulate consumption.

If prices long remain below cost the high cost operator will stop leasing and wildcatting; his flush production declines, and his contribution to the national supply diminishes. The same thing is true to a more limited extent of the operator of the middle class. The net result is a decline in production and an upward reaction in price. Operations are then renewed and the supply is increased. Drilling curtailment and the opening and closing of wells on account of price conditions are a recognition of the law of demand and supply. The history of crude oil production is the recurrence of these conditions.

The careful movement of prices in accordance with actual conditions of demand, supply and cost, and the balancing of the former two factors as nearly as humanly possible, will promote the best interests of industry and public.

The human equation and other factors that temporarily modify the law of demand and supply are too numerous for discussion in a paper of this sort. They must be weighed in measuring the oil situation.

Forecasting Demand and Supply

Oil men and investors are more interested in the future than the past. They must have predictions as the basis for policies and expenditures. The value of a forecast lies in the detailed effort and experience behind it. By applying practical methods to data now available it is possible to see around the next corner with a reasonable degree of accuracy during the greater part of the time.

As demand fluctuates less erratically than supply it can be more readily and accurately measured. The effect of the seasons and of price should be

carefully watched. A study of the consuming agencies and of detailed information on actual past demand should enable the engineer to make a forecast for one year that will not err more than 2 or 3 per cent. Estimates should be made for each product and domestic demand must be considered separately from exports. Quarterly data should be plotted on semilogarithmic paper for preceding years and a transparent scale used for comparing similar quarters in each year and making projections. The subject is too broad for detailed discussion here.

Under the competitive economic system, uncontrolled production is inherently characterized by extreme and erratic fluctuations, and supply is therefore more difficult to estimate than demand. The author is familiar with no method that has been tried for estimating beyond a period of more than a few months that has yielded results of practical value. The most satisfactory method the author has been able to devise for himself is based on a detailed study of separate pools or groups of pools with common characteristics. Explanation of the method was published in the proceedings[2] for 1926. Estimates made in this way for 90-day periods have not erred more than 2 per cent. His attempts to forecast for a longer period have not been successful. It is usually possible to foresee the trend for a slightly longer period.

The Shutdown Movement

The extensive movement in 1927 to control surplus petroleum production is well known. The evils that likewise accompany uncontrolled production are not new to the petroleum industry. Most of the remedies that have been presented appear impractical and hazardous. Economic experiments are far-reaching, costly and fraught with extreme danger. The cooperative curtailment of production and drilling during times of oversupply and the opening of closed or pinched-in wells during periods of overconsumption, appear to be the safest remedy that has been presented. Curtailed production has been practiced to some extent throughout almost the entire history of the industry. In comparatively recent years it has been resorted to in California and Wyoming. The present general shutdown program is more comprehensive.

The extensive experiment of 1927 is still under way. This shut-in program is necessarily the most important consideration in present estimates of production. The experiment has shown merit but no one can tell exactly at this time whether the operators will continue their agreements and the proration orders will hold in the courts of last resort. Consumption has passed supply during the season of peak demand and prices of some of the refined oils and of crude petroleum have been raised.

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[2] J. M. Sands and C. Osborn: Forecasting Petroleum Production. Petroleum Development and Technology in 1925, A. I. M. E. 750.

If the future position of the producers and the Government is broad-gaged and fair, the industry may triumph over many of the evils from which it now suffers.

Summary of Conclusions

1. Forecasting future prices is one of the principal problems of the oil man and engineer. Relationship of demand and supply are the principal factors. Costs, stocks, the human equation and the discovery factor are also important. The shutdown agreements will probably determine the trend of supply for the next few years.

2. The consumption of oil will continue its gradual increase during the next several years. Gasoline will be the leading product. Aviation may be expected to be a factor worthy of attention in a few years. Low prices for fuel oil should stimulate its use and thus help to absorb the surplus oil supply. As usual, demand will probably range a little less than 10 per cent. higher during the last six months of each year than during the first half.

3. The strong prices of 1918 to 1920 brought about improvements in methods of oil finding and production and in consequence the industry has been laboring under almost continuous oversupply since 1921.

4. Proved and actual production greatly exceed demand but control by agreement between producers and by Government regulation and aid seems to have become a factor in the oil situation. The overproduction of the past seven years appears to have proved to the producers the necessity of attempting to keep production within bounds.

5. So long as the shutdowns hold the situation will continue sound and prices of crude, though low, will be well supported. From the standpoint of costs, higher prices are justified.

6. Gasoline stocks are low, but the season of lean consumption will soon be here and prices may be expected to decline unless crude oil prices are raised.

7. Fuel oil is so cheap that consumption should increase and cracked gasoline can compete with other gasolines.

8. Potential production and proved, undrilled areas are so extensive that restricted production by cooperative agreement and proration seems to offer the only hope of improving conditions in the near future. Though there is the possibility that the agreements and proration orders may be upset, it seems probable that they will hold. Demoralizing prices would follow if the agreements were set aside.

9. Consumption will decline about 200,000 bbl. per day from the present figure during the winter and this additional quantity of oil must be shut-in if supply and demand are to be kept in balance.

10. All in all, the preponderance of the evidence is that, though from the standpoint of costs somewhat higher prices are justified for crude oil, production will be kept close to demand and prices will probably mark time until next spring or later.

Gasoline Economics and Refinery Operation

By H. J. Struth,* Houston, Texas

(New York Meeting, February, 1929)

Gasoline is undoubtedly of major importance not only to the petroleum refiner but to the producer. To study the economic aspects of gasoline is, in a measure, a constructive effort to solve the problem of overproduction not only for the refiner but for the entire petroleum industry. After all, the prime object of producing crude petroleum is to supply motor fuel and lubricants to nearly 25,000,000 American motor vehicles, not to mention the increasing demand for these products abroad. Since gasoline furnishes the chief source of revenue to the refiner, it follows that this important product should veritably become recognized by all branches of the petroleum industry as an almost infallible index of day to day requirements of the producer and the refiner. A careful study of gasoline statistics over the past decade or more reveals that there is a definite correlation between world-wide gasoline requirements and the demand for crude petroleum, as well as all other petroleum products. This leads the writer to the conclusion that gasoline is literally the economic yardstick of the entire petroleum industry.

Control of Operations

That the refiner has begun to recognize the urgent need for controlling his operations is evidenced by the results of the past three years. Unfortunately, it is a difficult problem to convince the refiner that he cannot run crude in excess of the demand for gasoline, without incurring a consequent decline in the market value of this and all other products of distillation. Undoubtedly, he still has much to learn in this respect. Few commercial products have enjoyed such phenomenal growth in demand as has gasoline, and, at the same time, few products have failed, as has gasoline, to reap financial benefit from the popular demand for a national necessity. Perhaps this unprecedented demand was responsible for the overextension of refining facilities, which resulted in the excesses of recent times; at any rate, as the demand for gasoline grew by leaps and bounds, so the refining industry continued to increase its capacity for

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crude. Naturally, when new refineries are built, those who operate existing plants are disinclined to reduce their crude runs in proportion to the increase in new refining capacity. This situation has undoubtedly created an artificial demand for crude petroleum, which spurred the

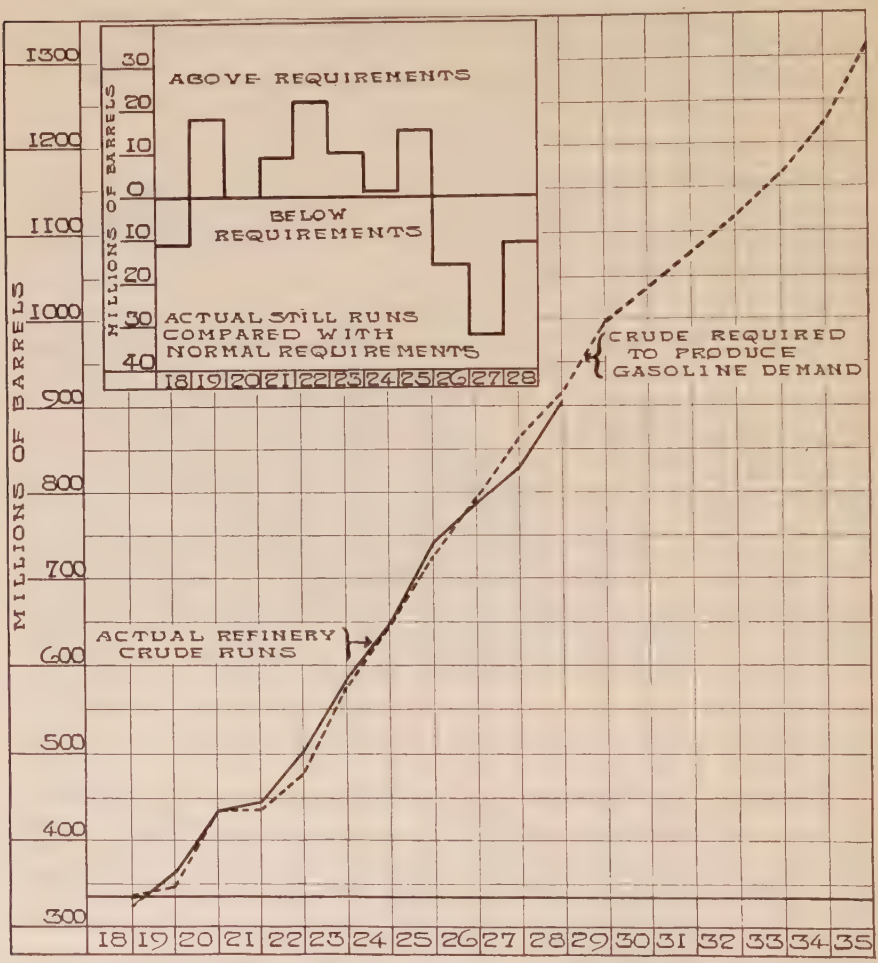

FIG. 1.—COURSE OF REFINERY CRUDE RUNS 1918 TO 1935.
Shows normal indicated run requirements and actual runs to date.

producer on to the inevitable chaotic conditions that confront the industry at the present time. The momentum of crude production, however, has made it exceedingly difficult to apply the brakes, while the momentum of overextension in refining capacity has brought about somewhat of a natural curtailment in the form of elimination, in which only the fittest have managed to survive.

During the past three years, 1926, 1927, 1928, there has been substantial evidence of effort on the part of the refining industry to prevent the continuation of overproduction. This fact is revealed by the statistics of still runs, compared with the normal quantity of crude required to produce the annual gasoline demand. Fig. 1 presents a graphic view of the refinery still-runs situation, showing the course of still runs and the exact status of refinery operations from 1918 to 1928. The insert contains an enlarged diagram of still-run operations compared with normal. The marked decline in gasoline stocks at refineries during 1928 furnishes a concrete example of the benefits that accrued to the refiner as a result of his efforts to control still-run operations. In Table 1 are shown the normal quantities of crude required to produce the gasoline demand for each year since 1918, compared with the actual annual refinery runs.

TABLE 1.—*Still Runs Compared with Normal*

Millions of Barrels

Year	Normal	Actual	Above Requirements	Below Requirements
1918	337	326		11
1919	348	362	18	
1920	434	434		
1921	434	443	9	
1922	479	501	22	
1923	571	581	10	
1924	643	644	1	
1925	725	740	15	
1926	795	779		16
1927	861	829		32
1928	917	906 (est.)		11

According to the record, the accumulated excess since 1918 represents a balance against the refining industry of 5,000,000 bbl. at the end of 1928. In other words, during the past three years, the refiner has succeeded in almost wiping out the unfavorable balance on his books. These facts suggest that refinery runs during 1928 should have been curtailed to the extent of at least 5,000,000 bbl. If this had been accomplished, stocks of gasoline would have been reduced nearly 2,000,000 bbl. more, a factor that would have lent a higher degree of stability to the market. As it is, however, the refining industry has entered 1929 in better condition than it has been in for a number of years, facing another record-breaking demand for its products. Whether the industry ends this year with a profit or a loss depends primarily on its ability to continue to keep its operations within reasonable bounds.

Future of Still Runs of Crude

Another point of equal interest brought out in this chart is the probable future course of still runs of crude in the refinery. By projecting the normal refinery requirements for crude through the year 1935, the writer has ascertained that the refinery demand for crude during that year will probably exceed 3,500,000 bbl. per day. Compared with the demand during 1928, this represents an increase of more than 1,000,000 bbl. of crude per day. In view of present and future field indications and the fact that our importations of South American oil will undoubtedly continue to grow larger each year, it is a foregone conclusion that the industry will experience no difficulty in obtaining an adequate supply of crude during 1935. In this connection, it is well to point out also that the refinery cracking process will continue to play a most important part. In fact, a glimpse into the future of the refining industry indicates that it will be decidedly uneconomical to operate a refinery without the cracking process. In projecting refinery requirements for crude through the year 1935, due consideration has been given to the necessity for increasing the industry's cracking facilities. The main deterrent to cracking up to the present time has no doubt been due to the extremity of overproduction in the producing branch of the petroleum industry. During the next few years, it is believed that proration will exert a more favorable influence upon the producer's situation and, consequently, bring the refinery cracking process into its own. If we consider the enormous demand for gasoline during the next few years, it becomes apparent that the refining industry must necessarily become better equipped with cracking facilities, or it will be literally swamped with fuel oil. Since every barrel of fuel oil represents from 12 to 15 gal. of potential gasoline, it must be conceded that each year makes it more imperative to crack the heavier products of distillation. However, as the output of cracked gasoline is increased, runs of crude must be proportionately reduced.

Value of Cracking Process

If it were not for the cracking process, there would undoubtedly be cause for great alarm over the immediate future supply of crude petroleum. Even if there were sufficient crude available to produce the future gasoline demand without the utilization of the cracking process, the industry would soon find itself unable to cope with the growing surplus of fuel oil. During 1928, the yield of gasoline from crude was about 38 per cent., as compared with 25 per cent. in 1918. Since the quantity of gasoline produced by straight distillation represented about 24 per cent. of the crude refined during 1928, it is obvious that cracking contributed an additional 14 per cent. Some idea of the present status of cracking

in the United States can be obtained from Fig. 2, which shows the percentage of gasoline recovery in the major refining districts during 1928. From this it is apparent that there is still plenty of room for expansion in the field of cracking. California is just beginning to utilize cracking as a means of increasing the yield of gasoline from crude. With the possible exception of Indiana-Illinois and the Rocky Mountain districts, this picture suggests considerable future expansion in the utilization of cracking plants. At the present rate of increase in demand for gasoline, the petroleum industry will be obliged to supply a demand of approximately 715,000,000 bbl. during the year 1935. This means that

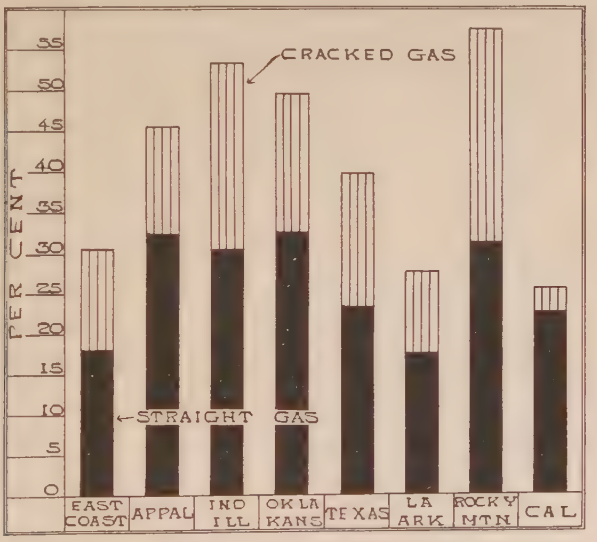

FIG. 2.—STATUS OF CRACKING OPERATIONS DURING 1928.
Percentage of gasoline yield from crude, showing proportion produced by straight distillation and by cracking plants.

about 645,000,000 bbl. of this supply must be produced directly from crude petroleum, the remainder representing natural gasoline. Allowing for a normal increase in cracking facilities during the intervening years, the writer finds that the average yield of gasoline per barrel of crude, for the entire industry, will average approximately 49.2 per cent. during 1935. This calls for a normal refinery demand for crude of about 1,310,-970,000 bbl., or an average of about 3,592,000 bbl. daily.

Gasoline Supply and Demand

Fig. 3 presents a graphic view of the monthly gasoline supply and domestic demand during the past few years. In this chart, the facts are expressed in terms of gallons per average motor vehicle registered. It

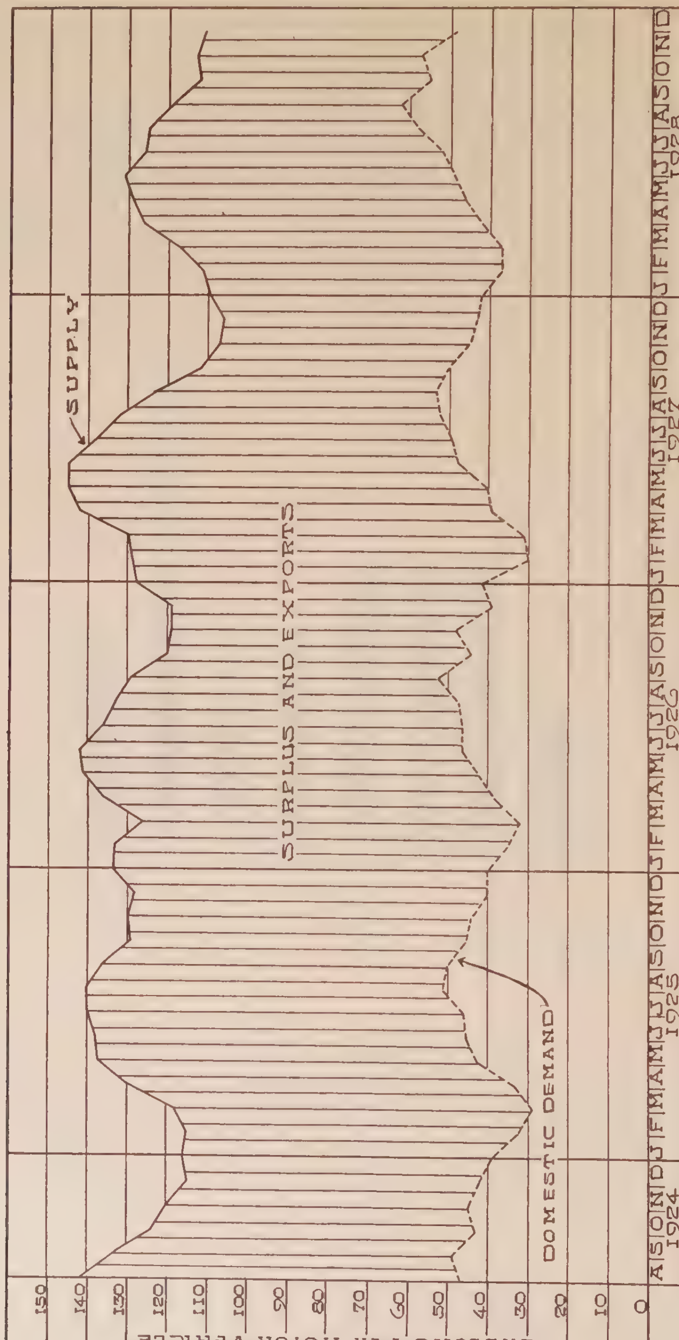

FIG. 3.—Supply and domestic demand of gasoline, expressed in gallons per motor vehicle.

will be noted that the area between supply and demand has narrowed considerably, particularly during the past year, clearly indicating the marked improvement that has taken place in refinery operations. On Dec. 1, 1928, refinery stock of gasoline represented 54 gal. per motor vehicle, while during the month of November the total supply, stocks plus production, represented about 111 gal. per motor vehicle. Although the demand during the month of November had declined from 57 gal. in the preceding month to 49 gal., the surplus for that month represented only about 62 gal., of which approximately 13 gal. was exported. While, in reality, the refinery gasoline-supply situation reflected considerable improvement during 1928, with stocks relatively lower throughout the year than for quite a number of years, the facts reveal that the situation on Dec. 1, 1928, stood at relatively the same level as on Dec. 1, 1927. There is no doubt that further improvement would have been witnessed if refiners had reduced crude runs in conformity with the increase in the output of cracked gasoline. Table 2 shows production, domestic demand and stocks of gasoline in gallons per motor vehicle for the first 11 months of 1928.

TABLE 2.—*Refinery Gasoline Situation during* 1928

Gallons per Motor Vehicle

Month	Production	Domestic Consumption	Stocks
January	52	39	67
February	50	39	72
March	54	44	75
April	54	48	74
May	57	51	69
June	57	54	64
July	61	58	56
August	63	62	50
September	62	55	49
October	64	57	49
November	62	49	54

One of the most interesting facts revealed by this study is that the average annual consumption of gasoline per motor vehicle has shown a marked increase during the past few years, as follows: in 1924, 464 gal.; 1925, 497 gal.; 1926, 526 gal.; 1927, 545 gal.; 1928, 604 gal. While a considerable quantity of gasoline is consumed for purposes other than the operation of motor vehicles, these facts show that a marked change is taking place in the annual motor-vehicle demand. This emphasizes a number of important developments: (1) the popularity of the closed, all-weather motor car; (2) the marked increase in the number of motor-bus lines; (3) the constantly increasing mileage of surfaced highways

throughout the United States. In previous articles on this particular phase of the gasoline situation, the writer has brought out facts to prove that the closed motor vehicle is exerting a marked influence on the seasonal demand for gasoline, while the motor bus is accelerating the demand for gasoline and also tending to bridge the gap between winter and summer demand. The combination of closed cars, motor buses and improved highway mileage is rapidly eliminating the former seasonal variations in the gasoline market of the United States.

Price Variations of Gasoline

While many reasons are advanced for fluctuations in the price of gasoline, the chief underlying reason is the influence of supply and demand. Since the gasoline demand has been growing consistently larger each year, it is obvious that there is nothing wrong with the demand. A study of supply-demand ratios over a period of several years emphasizes the need for better control over the supply, not only of gasoline, but of crude as well. While the refiner is in a position to exercise control over his own supply situation, he is, nevertheless, confronted also by the good or bad influence of the crude producer's supply situation.

Some idea of the effect of supply-demand ratios on the price of gasoline can be obtained from Fig. 4, which shows the trend of Oklahoma, Pennsylvania and California motor-gasoline prices in relation to the supply-demand ratios of both gasoline and crude petroleum. In constructing the ratio of gasoline plus the influence of the crude supply, it was necessary to consider the visible gasoline supply; *i. e.*, the quantity of potential gasoline available from the current crude supply, plus the actual supply of gasoline at refineries. Thus, the solid step-curve represents the supply-demand ratio of visible gasoline, in crude and at refineries, while the broken step-curve represents the supply-demand ratio of actual gasoline only. Since all factors of supply and price have been computed on a relative index-number basis, the chart shows a striking relation between the actual and potential supply and the market prices of gasoline. It will be noted that where the supply-demand ratios of actual and potential gasoline coincide in movement, the price of gasoline conforms somewhat to the rise and fall of the barometer, as was the case during 1926.

Where improvement is indicated in the refinery gasoline-supply situation and there is a decided reversal of form in the crude situation, the price of gasoline has a tendency to sag. The effect of excessive crude production during the early part of 1927 illustrates that, even though the refinery gasoline situation shows marked improvement, the influence of overproduction and excessive supply in the producing branch of the industry has a tendency to keep the gasoline market in a state of depres-

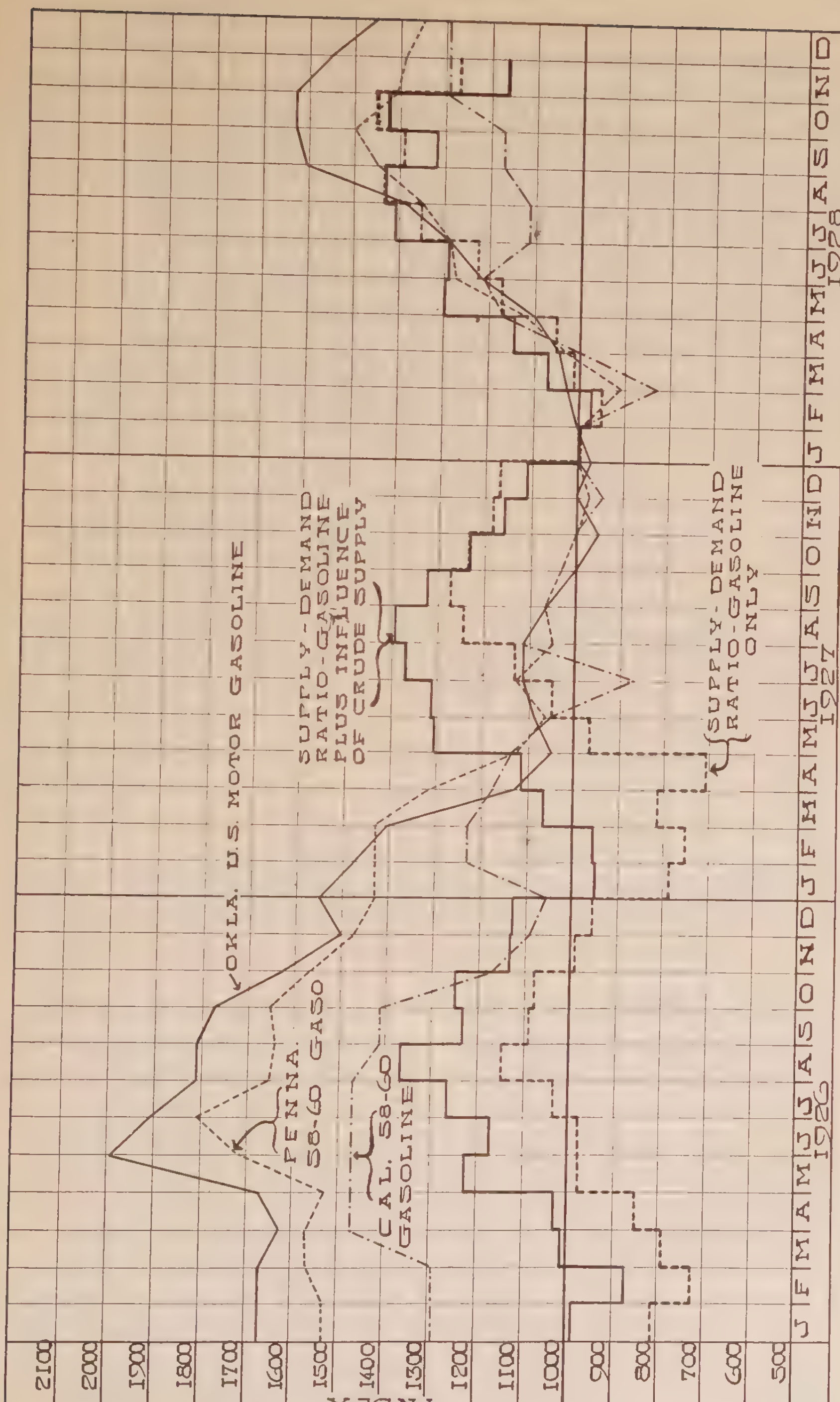

FIG. 4.—EFFECT OF SUPPLY-DEMAND RATIO ON REFINERY PRICE OF GASOLINE, WITH AND WITHOUT INFLUENCE OF CRUDE.

sion. A review of refinery gasoline statistics for the year 1927 leads to the conclusion that, although the refiner managed to curtail his crude runs somewhat, he did not curtail them in conformity with the increased output of cracked gasoline. Thus, while there was some improvement, the total output of gasoline was still in excess of requirements, which, combined with an unsatisfactory crude situation, resulted in a sagging gasoline market toward the end of the year.

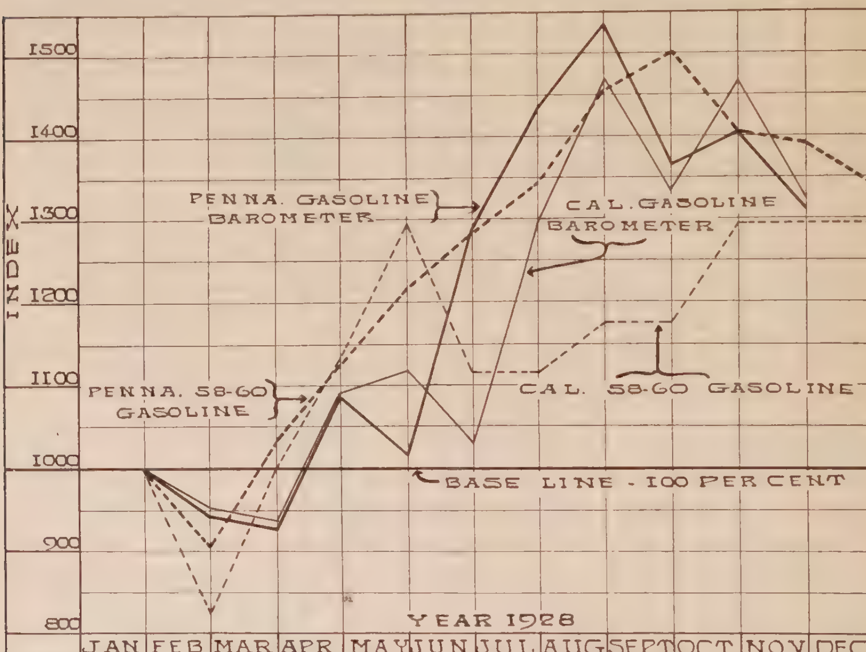

FIG. 5.—HOW THE GASOLINE PRICE BAROMETER COMPARES WITH THE GASOLINE MARKET IN PENNSYLVANIA AND CALIFORNIA.

The year 1928 shows a high degree of relativity between the supply-demand ratios and the price of gasoline. Improvement in both barometers was directly responsible for the improved market tone which prevailed for gasoline during last year. During the latter part of the year, however, another unfavorable turn in the crude situation and the effect of an output of gasoline somewhat higher than necessary indicated a weakening gasoline market. For example, the potential and actual supply of gasoline during November of last year was approximately 248,900,000 bbl., while the actual demand was 30,900,000 bbl., representing a supply-demand ratio of 0.1241. Actually, the gasoline supply at refineries during November was 59,975,000 bbl., and the demand 30,900,000 bbl., representing a supply-demand ratio of 0.1268. In April, 1927, the potential and actual supply of gasoline was 226,137,000 bbl., with an

actual demand of 26,985,000 bbl., giving a ratio of 0.1193. During that month the actual gasoline supply at refineries was 79,364,000 bbl., demand 26,985,000 bbl., giving a ratio of 0.3400. The difference in market prices of gasoline for those two periods clearly illustrates the influence of the crude situation upon the refinery gasoline market. Fig. 5 exemplifies the marked relation between the supply-demand ratios of actual and potential gasoline and the market prices of California and Pennsylvania gasoline during 1928. A study of these facts for individual refining areas of the United States would reveal an even closer relation than is shown in the accompanying charts. The fact remains, however, that the price of gasoline is primarily controlled by the ratio of supply to demand, being superior to all other reasons advanced for market fluctuations.

Effect of Demand for Gasoline

The main function of this paper is to give conclusive evidence to the theory that demand for gasoline furnishes a most reliable index of the demand for crude petroleum as well as all other products of the petroleum industry. If efforts to prorate petroleum production meet with success, as they apparently will, in time, it is believed that the immediate and future demand for gasoline will furnish a sound basis for controlling the above-ground supply of petroleum. For a number of years, the writer has calculated the gasoline demand in advance and has proved that it is possible on this basis to gage the normal demand for crude with remarkable accuracy. With all the valuable facts that are available to the industry, it is possible to predict accurately, well in advance, the quantity of gasoline required for domestic and foreign consumption, the anticipated yield of gasoline from crude, the normal quantity of crude required by our refineries, and even the approximate quantities of crude required for export and for use as bunker fuel. Thus it is evident that the producing branch of the petroleum industry should give serious consideration to demand for gasoline as a reliable barometer for gaging immediate and future requirements from the various and combined producing areas of the country.

To the refiner, demand for gasoline furnishes an extremely accurate index upon which to base still-run schedules and general refinery operation. Advance estimates of gasoline shipments and probable gasoline recovery from crude distillation, taking into account the degree of utilization of the cracking process and the quantity of gasoline in storage, furnishes the most reliable basis upon which to maintain a normal individual operating schedule. For the refining industry as a whole, the course of the immediate future lies in obtaining the greatest possible yield of gasoline from every barrel of crude run to stills, thereby avoiding

the accumulation of excessive fuel-oil stocks, and maintaining a still-run schedule that will conform within reasonable limits to the demand for gasoline.

The chief danger, however, is the possibility of further overextension in refining facilities. When we consider the ease with which the industry can increase the output of petroleum products, it becomes apparent that additional refining plants are not needed, unless they replace obsolete equipment. In this respect, however, I fail to agree with those who insist that the industry is doing too much cracking. On the contrary, I believe that the industry is not doing enough cracking to insure economic utilization of existing petroleum supplies. Of course, as cracking facilities are expanded, there must necessarily be a proportionate tapering off in the quantity of crude run to stills. In the final analysis, it all resolves into the basic fact that demand for gasoline should be the medium upon which to base present and future operations not crude capacity.

It is possible for the refiner to control his operations along the lines suggested, and, in the future, it may be possible also for the producing branch of the industry to control the output of crude petroleum along the same lines. If it were possible for the entire petroleum industry to keep output within the limits prescribed by the demand for gasoline, it is a foregone conclusion that every branch of the industry would be able to conduct its operations on a profitable basis.

DISCUSSION

H. J. Struth.—I made some estimates on what the probable consumption of gasoline would be this year and how much crude would be required. I estimate that by the end of 1929, we will have 28,000,000 motor vehicles in the United States. I figure that this year there will be a monthly average of 26,750,000 motor vehicles in the United States. Since our total gasoline demand this year will represent an average of about 610 gal. per motor vehicle, taking into consideration domestic demand and other use, that will aggregate 388,000,000 bbl. of gasoline for domestic consumption. We will probably export 55,000,000 bbl. That makes a total of 443,000,000 bbl. of gasoline as the total demand for 1929. Of that quantity, 50,000,000 bbl. will consist of natural gasoline, which leaves a total to be produced from crude of 393,000,000 bbl. Undoubtedly the recovery of gasoline from crude will be increased, possibly 2 per cent. That means we will probably produce 39.5 per cent. from every barrel of crude. That would spell a demand for crude of 995,000,000 barrels.

We will probably import 100,000,000 barrels this year—it certainly looks that way, judging from present receipts of South American oil and it is possible we will export 20,000,000. That leaves a net of 80,000,000, bbl. If we deduct that from the total of 995,000,000, that leaves 915,000,000 bbl. for the producers in America to market. That is 13,000,000 bbl. more than was actually produced last year. In other words, our daily average production this year must not exceed 2,500,000 bbl. per day. If it does, the industry will suffer further depression.

C. Osborn.*—Those who follow the economics of the oil business know that during the past two or three years, in the face of oversupplies of crude most of the time, overabundant refining capacity, and oversupply of fuel oil from which additional gasoline could have been cracked, the refiner has restrained himself somewhat, and

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contrary to his practice during the years prior to the last two or three, has made a little money out of refinery operations.

J. E. THOMAS,* Fort Worth, Texas.—I feel that there will be an oversupply of gasoline in 1929, and that it will be underpriced. Mr. Struth pointed out correctly that more progress could be made in the cracking situation in California. However, it will not be made, because California has no coal. There is a healthy demand for fuel oil. In order to manufacture a sufficient supply of fuel oil it is necessary to manufacture an excess of gasoline. Therefore, to crack fuel oil in California would burden their present problem. To supply the necessary consumptive demand for fuel oil, if the Pacific Coast in 1928 required the overmanufacture of 78,000 bbl. a day of gasoline (which was simply dumped on the Eastern seaboard because of the increase in gravity of the crude runs to stills) it will require an overmanufacture of 88,000 bbl. per day in 1929, for which reason you need anticipate no advance in cracking operations in California.

C. OSBORN.—Mr. Struth, you made no mention of comparative profits from gasoline operations in 1928 and 1929. What is your opinion with regard to what the refiners may expect in the way of profit from gasoline manufacture in 1929?

H. J. STRUTH.—I think that what the refiner has to do is not to run an excessive quantity of crude. He must get all he possibly can out of every barrel of crude run. That means to utilize his cracking process to the fullest extent. The refiner cannot solve the problem of the producer by running excessive amounts of crude. He will spoil his own market and get such an excessive supply of all products that he will not know what to do with it. As a result, the market will become demoralized. The refiner should operate independently of the producing situation.

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* Petroleum Analyst, Fenner & Beane.

Fuel Oil, the Safety Valve of the Petroleum Industry

By Charles J. Deegan,* Ponca City, Okla.

(New York Meeting, February, 1929)

The purpose of this paper is to point out some features of the position of fuel oil and its relationship to the economic balance and price structure of the petroleum industry. The term "fuel oil" as used in this paper includes crude used as fuel as well as refined gas oil and fuel oil. The period covered, from 1922 to date, may be characterized as the new normal era after the post-war inflation and deflation. In order to establish a proper perspective, the figures on consumption of the principal products of petroleum are shown in Table 1.

Table 1.—*Principal Items in Petroleum Consumption*

Thousands of Barrels per Day

	1922[a]	1928[a]	Increase
Fuel oil	880	1,220	340
Gasoline	388	1,046	658
Kerosene	151	162	11
Lubricants	64	95	31
Crude exports	30	52	22
Refining losses	51	80	29
Total[b]	1,564	2,655	1,091

[a] Daily average for period January to October inclusive.
[b] Does not include wax, coke, asphalt and "other finished products."

This table shows that fuel oil and gasoline made up the bulk of the total demand in 1928 just as they did in 1922. There has been so much comment about the enormous increase in gasoline consumption that it may come as a surprise to some people to find that fuel oil is still at the head of the consumption list, in point of volume at least, and seems likely to hold that place for at least another year. Having established the fact that gasoline and fuel oil are by far the most important products, the remainder of this paper will deal almost entirely with these two items.

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Law of Marginal Utility

It becomes necessary at this point to introduce what the economists call "The Law of Marginal Utility." This means simply that for any given article at a given price there is a certain number of people who feel that they can afford to buy the article and do so. If the price of the article can be reduced, a larger number of people can afford to buy it and will do so. One of the best examples of this in recent years is the automobile. Everybody knows that the price of automobiles has been reduced again and again during the past 10 years. Everybody also knows that if the prices of automobiles were as high at the present time as they were 10 years ago, not nearly so many people could afford to buy them. On the other hand, some articles are so cheap that reducing prices would not increase the consumption materially because people can afford to use about all they have any need for at present prices. A good example of this would be common salt. These two examples might be called the two extremes. One of the objectives of this paper is to draw a parallel between the automobile and fuel oil on the one hand and between gasoline and salt on the other.

It is improbable that automobile owners or other users have ever deliberately curtailed their purchases of gasoline at any time during the past seven years on account of high prices. There have been cases of regional depression due to local industrial conditions but it is doubtful whether any more economy was practiced in gasoline consumption than in the general scale of living, even at such times. On the other hand, it is just as doubtful that extremely low prices have ever stimulated consumption to any material extent. Automobile owners seem to drive their cars when they need them, regardless of the price of gasoline. One reason for this, of course, is the fact that there is no satisfactory substitute for gasoline, at least at a lower price, but it is also true that the price of gasoline during the past seven years, even at its highest point, has never been high enough to make any material difference to the people who used it. The reason is that anyone who can afford to own a car or truck and keep it running can rather easily afford to pay the price asked for gasoline. Therefore price had little to do with the amount sold. This, of course, does not apply to the sales manager who cuts the price in order to persuade a possible customer to purchase "A" company's gasoline instead of "B" company's. It does mean that in the end the combined marketing departments of the industry have sold no more gasoline than they would have sold at a somewhat higher price. We say, therefore, that the consumption of gasoline in relation to its price is comparable with the demand for salt.

The parallel between the automobile and fuel oil is easily drawn and the conditions are almost exactly the reverse of those prevailing with

regard to gasoline. For transportation a man has a choice of several methods; he can walk, ride a bicycle, use a horse, street cars, railroad trains or busses. If the cost of the automobile is low enough to make its advantages over other means of transportation worth while, he will buy it. Most of the prospective users of fuel oil can use some grade of coal, coke, tar or gas. If the cost of fuel oil is low enough in proportion to its advantages as compared with other fuels, they will buy fuel oil.

Uses for Fuel Oil

The purposes for which fuel oil is used are more numerous than those for gasoline. The amount consumed also is greater, but unlike that of

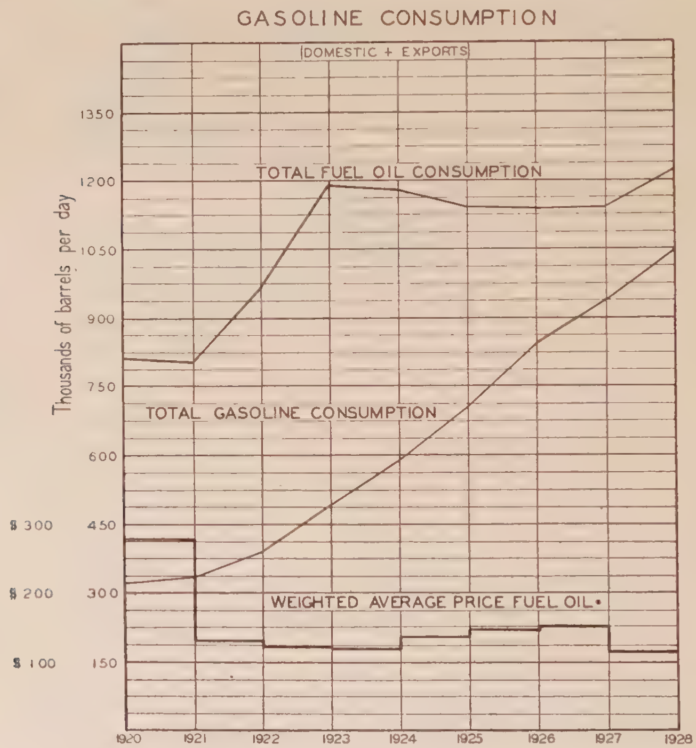

Fig. 1.—Total fuel oil consumption vs. gasoline consumption.
*Courtesy of Joseph E. Pogue.

gasoline, fuel-oil consumption can be increased considerably at any time by a reduction in price and an aggressive sales campaign. The potential market for fuels of all kinds for general heating purposes is much larger than the entire output of fuel oil. There are, however, satisfactory substitutes for these purposes in the form of coal and other fuels. The

extent to which oil replaces these other fuels depends on relative price and sales efforts. Numerous cases in the past seven years have shown that many users of large amounts of fuel have at various times changed from coal to oil and vice versa, the direction of change depending almost entirely on the relative prices of the two products. It is obvious that this means a flexible and fluctuating demand for fuel oil.

There are various uses for fuel oil in which it has marked advantages over other fuels and some in which it has practically no competition. For instance, it has a distinct advantage over other fuels in marine uses, on railroads in certain parts of the country, and so forth. Without going into detail, it may be said that it has a large market from year to year in which it maintains its advantages over all other fuels. This market forms the backlog of fuel-oil consumption. In addition to this backlog, there is a rather large portion of fuel oil constantly going into a highly competitive market. This market is a battleground and the amount captured by fuel oil rises and falls with its price changes in relation to other fuels. Fig. 1 illustrates the difference between the rate of growth in gasoline consumption and the rate of growth in fuel oil consumption.

Fuel Oil as Safety Valve

It will be noted that gasoline consumption follows a more or less steady trend, regardless of the general condition of the petroleum industry. The reasons for this have already been given. Fuel oil displays no such steady trend. The total consumption in general rises and falls in accord with the amount of overproduction of crude oil in the industry. There is a definite relationship between total fuel-oil consumption and the balance between total petroleum supply versus total petroleum demand. When overproduction of crude oil brings the price structure of the industry down with a crash, the low prices stimulate the consumption of fuel oil and relieve the strain. When the supply of crude oil is insufficient to meet the demand, prices go up and fuel oil is driven from a part of its highly competitive market, thereby easing the strain on the demand for crude oil. This function of fuel oil gives rise to the title of this paper—Fuel Oil, the Safety Valve of the Petroleum Industry.

It is apparent that this safety valve does not always open as soon as it should, although it generally closes on schedule. This is probably due to the fact that this highly competitive portion of the market belongs normally to the coal industry, at least to a greater extent than it does to the petroleum industry. Therefore it probably requires more sales efforts and price reductions from the petroleum industry than from the coal industry. Hence, although a share of this market can be captured by the fuel-oil marketers through vigorous exertion, at the slightest relaxation in economic pressure it tends to revert to the coal marketers.

Price Control

The manner in which the expansion and contraction of fuel-oil consumption acts as a safety valve in time of overproduction has been shown. The thing that interests most people, however, is what influence this may have on the price of crude oil and refined products. On the basis of statistics, it seems safe to assume that by and large the factor that controls crude prices and ultimately refined product prices is the amount of crude going into or coming out of storage. The difference between an addition of 100,000 bbl. of crude oil per day to storage, and the withdrawal of the same amount, is roughly a difference of 75 c. per barrel in the price of Mid-Continent crude. It seems obvious, therefore, that prices and profits in the petroleum industry depend very largely on the volume of a relatively small surplus or shortage in supply. Since we are assuming that gasoline demand at any given time is practically fixed regardless of price, the burden of absorbing a surplus of production or reducing a shortage falls inevitably on fuel oil. Since we have seen that it seldom fails to react quickly to a shortage of crude oil, it is obvious that its effect in times of overproduction depends on how much of the surplus it can absorb and how quickly it can do so.

It seems to have dawned on the refiners as a group in 1928 that there was no necessity for their suffering because of the sins of the producers. The year 1928 has therefore witnessed a paradox. Despite overproduction of crude, gasoline production has been held slightly below demand and stocks have been reduced. The result has been a price for gasoline that afforded a slight margin of profit. Prices of fuel oil, on the other hand, were reduced greatly in order to expand the market and lighten the storage burden. But with cheap fuel oil and a slight profit in gasoline, there has been a constant temptation to reduce runs of fresh crude and expand cracking operations. Up to October, it must be said that the temptation has been marvelously resisted, for the percentage yield from crude has been practically normal or even slightly below.

Of course, if the temptation should become too strong and a large group of refiners should yield, the profit would be only temporary and chaos would soon result. Such action would react on the delicately balanced price structure in two ways. The reduced demand for crude would soon result in another price cut and further demoralization in the ranks of the producers. On the other hand, the increased demand for fuel oil for cracking would tend to increase prices and allow coal to drive it from a portion of its present markets. This would reduce the total demand for petroleum products, which would reflect back on the price of crude oil and that of all refined products. Then we would have 1927 all over again. It is to be hoped that the refiners will realize that so long as they can refrain from yielding to the temptation of cheap fuel

oil, just so long and no longer can they hope to keep their delicately balanced price structure and continue to eke out a bit of profit from operations.

Fuel Oil and Conservation

We have heard considerable criticism in the past few years about the economic waste of burning oil for fuel in places where coal or some other fuel would serve the same purpose. It would be folly of the rankest kind to ignore the rising tide of public opinion about conservation; it is too vast a movement, and in many cases well founded. Conservation applies to other industries as well as to the petroleum and is gradually becoming a national shibboleth. Since we cannot ignore it, we must use a little common sense in considering its application. There is no true conservation in wrecking the economic foundations of an existing major industry because of a vague and nebulous idea as to the needs of future generations. The use of fuel oil in industries where coal would serve is not going to be stopped in sudden and ruthless fashion by legislative fiat in the name of conservation; it is going to cease gradually as the result of economic law operating through a variety of channels. True conservation consists of the most complete utilization of a given amount of a commodity in the satisfaction of human needs.

There are at least two factors that are going to affect seriously the future of fuel oil and tend to bring about true conservation. These two factors may develop simultaneously, or one may cause the other to develop. The one factor that is sure to come is ever-increasing efficiency on the part of the coal industry. At present, the coal industry is attacking its problem along two lines simultaneously. One line is a study of ways and means to increase the efficiency of utilization of coal in its present channels of consumption. We may rest assured that the coal men will find ways and means of making efficient heat units cost their customers less money. The other line is a scientific study to find new uses for coal. We may be equally certain that the time and effort now being devoted by internationally known scientists will bear fruit and that many new products and uses will be developed for coal. These new uses and by-products will probably act as by-products usually do—reduce the cost of the main product and likewise its sale price.

The other factor that will tend to bring conservation is simply a parallel development by the petroleum industry with regard to fuel oil, aided and assisted by developments in the internal-combustion engine. We also must aid our customers to obtain efficient heat units at a lower cost, and at the same time we must put our scientists to work to find and develop those myriad by-products which they claim it is theoretically possible to make from petroleum. In our case, we shall inevitably find that in certain fields we can obtain such a great advantage over coal

that it will pay us to concentrate our efforts on enlarging these markets, gradually abandoning those in which our margin of superiority over coal is so small that a very slight change in relative prices will wipe it out. Thus it will eventually come about that, through economic evolution instead of revolution, all those things so ardently desired by conservationists today will have been accomplished.

Effect of New Inventions

As an example of future possibilities, consider recent developments in the Diesel engine. The Packard Motor Co. has, on the verge of commercial success, a Diesel engine weighing only about 3 lb. per horsepower. This engine is being used experimentally in an airplane. For fuel the company claims to have successfully used a product as low as 26° gravity fuel oil, although for the most part a distillate of somewhat higher gravity has been employed. It takes little imagination to see that if a Diesel engine satisfactory for airplanes can be developed, it can also be used in automobiles. On the other hand, certain oil companies are now putting on the market a pure, stabilized casinghead or natural gasoline, both for automobile and airplane use, for which they claim certain superior properties. The question then arises: What is the future motor fuel going to be?

It is a peculiar characteristic of many new inventions that they seldom drive out the old order altogether. Thus we still have steam engines working away merrily in spite of our internal-combustion engines and electric motors. If this condition continues to hold true, we can look into that not too distant future and see our refineries turning out, not two or three grades of gasoline and perhaps one or two of Diesel oil, but a whole gamut of motor fuels for all kinds of internal-combustion engines, ranging from the lightest gasoline to a rather heavy distillate, well down into the fuel-oil cut. In addition to these conditions, we shall have been forced into chemical research for new products and will undoubtedly have found them. So we shall also be turning out quite a varied group of chemical by-products. It looks as though the future refinery is going to be a very complicated factory and we ought to have a little sympathy for those who are going to have to work out the complicated price structure of that not too distant future.

Recommendations to the Fuel-oil Industry

No paper is complete without a list of recommendations of the things to be done by the patient if he is to survive. Our recommendations will be few and, we hope, brief, but, in the vernacular, "they take in a lot of territory."

1. We urgently recommend to the refiners that they consider carefully their present delicately balanced price structure and gird themselves against the temptation to flood the market with gasoline from cheap fuel oil. The consequences will be fully revealed in red ink on the books.

2. We urge the industry to realize that curbing overproduction by artificial means is only the first step. It should be obvious by this time that mere proration and shutdown agreements can only result in a constantly mounting potential production held back. It is like a dam which must be constantly built higher and higher because the average inflow exceeds the average outlet. Therefore, proration inevitably calls for a supplementary action toward developing new markets and increasing consumption.

3. The work to increase consumption should be divided into two parts: (*a*) intensive analysis of present markets for possibilities of expansion, also a study of possible new uses for present products; (*b*) research for new products from petroleum and particularly from the fuel-oil fraction. Our present research expenditures seem to be directed entirely toward increasing the supply of crude oil and the yield of gasoline. These expenditures result only in adding to the burden of over production and further breaking of the price structure. We have heard the plea that the saturated chain hydrocarbons of petroleum are much more difficult to alter than the ring-type hydrocarbons of coal. We cannot help thinking that if some of the millons spent on geophysics, gas-lift and cracking processes had been spent on research for new products, perhaps the saturated hydrocarbons might not be considered so difficult to alter. We still find that it is easier to persuade oil companies to make an appropriation to help break price structures and reduce their own profits than one to help maintain prices and add to profits.

DISCUSSION

C. Osborn,* Tulsa, Okla.—Probably a good many people do not agree with many statements made in this paper. Having in mind the overproduction of crude oil, which will apparently continue for some time, and the oversupply of fuel oil which will result, the price of fuel oil undoubtedly will continue to be low and the refiner must find an outlet for it for inferior uses. This brings him directly in competition with the bituminous coal industry. It would be interesting to know, looking at the situation from the standpoint of an oil man, what the outlook is with respect to prices of bituminous coal for the next year or two.

A. T. Shurick,† New York, N. Y.—The price of coal is our main trouble. We ran into that in 1924 when the base scale was increased to $7.50 per day. Then the price of coal jumped clear out of sight and our troubles began. That was the time when our consumption deficits began to develop. That scale has been reduced from $7.50 to $6. The union efforts to maintain the former scale were seriously jeopardizing its whole existence. The price of coal is being reflected in that changed

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† Consulting Mining Engineer.

condition. Our prices are getting down to a more stable economic level and we are hoping that that will cause some increase in the consumption. However, the fact remains that the consumer has been educated now into fuel-economy lines and he is not going to drop that overnight.

In the course of our study we found that a certain trunk line railroad used an average of 4½ lb. per indicated horsepower to the drawbar. New types of locomotives put in service last year are using 2¼ lb. The railroads are the largest individual consumers of coal. They use about 28 per cent. of all the coal produced at the present time from bituminous coal mines. The average consumption for all motive power is 4½ lb., and they have locomotives working on the line today under conditions of practical operation (not theoretical, not models or under design) only using 2¼ lb. You can appreciate how serious that is to us with our largest individual consumer of coal in a position to cut his coal consumption in two any time he wants to.

You might say that they could not afford to do it. We analyzed that. The railroad investment in motive power alone amounts to only about 8 per cent. of the total investment. Fuel is the second largest item of expense; next to labor, it is the principal item of expense. Should the roads decide to scrap every piece of motive power on their lines that would only be 8 per cent. of the total investment. By doing that they would immediately cut their second largest item of expense in two.

I gather that Mr. Deegan believes that there are rapid changes from coal to fuel oil, or vice versa. His paper seems to indicate that in several points. That is not what we have found out in our studies. We believe that that conversion is slow and very deliberate. A man who has a fuel-oil furnace cannot immediately turn to coal if the price of fuel oil jumps up a few cents; he will probably drag along for a year or two hoping that the price will come down. In fact, we believe that the oil people get most of their business in new installations rather than in conversions of existing plants from coal to fuel oil.

The author seems to feel that the coal men are getting more business than I really believe we are getting. He says, "At present, the coal industry is attacking its problem along two lines simultaneously. One line is a study of ways and means to increase the efficiency of utilization of coal in its present channels of consumption." The coal industry, ever since its inception, has taken the position that our responsibility for the coal ended when we put it on the railroad cars. That means that we endeavor to prepare it, size it, clean it, wash it and treat it in whatever way is necessary. A good many coal consumers say that we do not do it, but we do the best we can. From that point on, however, we have not accepted any responsibility. A good parallel is the difference between the farmer who produces the crops and the grocery man who sells them. There is just that much difference between the producing of coal and the marketing or use of it.

"The other line is a scientific study to find new uses for coal." I think the same thing applies to that. Fundamentally, our industry is not equipped to go into those more delicate, highly technical phases. We are a rough and ready industry, inherently and traditionally confined to heavy, rough work. We might be compared with a big steam shovel working on an excavating job as opposed to the consuming end, say at a gas plant where they have very highly skilled technical help. There is hardly any comparison there. I really do not see very much hope for us in that direction.

The author has not made a very apt comparison in the consumption of gasoline in relation to its price being comparable with the demand for salt. Taking the practice abroad, as I recollect—I took a motor trip in England two or three years ago—the price of gas is a couple of shillings per gallon, around 45 or 50 cents. That has made quite a difference in the motor practice over there. I sat with the chauffeur part of the time and he showed me the mechanism of the car, which had six or eight different

shifts. Instead of jumping from low to medium and high, there are four or five intermediate shifts to use in climbing a hill, for the specific purpose of economizing on gas. A great many people use motorcycles there whereas in this country those in the same station would not think of using them. That indicates to me that salt in comparison is not very apt. I think there will be marked and important economies in the use of gas as the price goes up.

In conclusion, I can only subscribe to what the author says: "We cannot help thinking that if some of the millions spent on geophysics, gas-lift and cracking processes had been spent on research for new products, perhaps the saturated hydrocarbons might not be considered so difficult to alter."

R. H. Johnson,* Pittsburgh, Pa.—In the matter of demand, it seems to me the author has not taken into consideration two large and increasing classes of large unit consumers; namely, the taxicab and the interurban bus and moving services. These companies are bound be concerned with fuel economy and I think they will look with considerable interest to experiments in the direction of Dieselization and anything that can be done in that way will greatly interest some of them. I think we may safely infer that progress in the direction of fuel economy will come from the largest consumers. They have the greatest incentive and usually have better staffs by which such attention can be directed. If the present tendency in the increase of taxicabs and interurban service continues, certainly the marginal utility situation will be altered. In the past, the situation has been nearly as the author has stated.

Diversion of more research to utilization as he suggests cannot proceed as rapidly as he would like. Research in the directions which he disapproves gives the company an immediate and direct advantage, whereas the other researches are more for the benefit of the industry as a whole. That type of research has always relatively lagged and always will; for most of it we must look to institutions like the American Petroleum Institute and governmental funds and some of the larger companies that can afford to make a disproportionate contribution to industry as a whole in their research appropriation.

C. J. Deegan (written discussion).—Mr. Shurick says that the parallel between gasoline and salt was not a good example in so far as conditions in Europe are concerned. That is true—the comparison was intended to apply only to the United States. The point was not clearly defined as to the geographical limitations of its application and Mr. Shurick was justified in his exception.

On the other hand, Mr. Shurick claims that the coal industry is a rough and ready one, regarding its field as confined to the production of the raw material. In spite of this contention, a considerable portion of his discussion is devoted to increased efficiency in the utilization of coal by some of the largest consumers. The misunderstanding here seems to be that Mr. Shurick regards the "coal industry" as referring only to the producing branch, whereas the author considered it in the broader sense of including all branches. Mr. Shurick further disclaims the efforts of the coal industry to develop new products and new uses. Quite possibly he does not consider the recent international conference at Pittsburgh as a part of the coal industry, but from an economic standpoint it certainly looks like a quite definite part of the coal industry, particularly to the petroleum industry, which sees possibilities of revolutionizing influences arising out of the work of these conferences.

Professor Johnson takes the stand that progress toward research for new products cannot proceed rapidly because it will not yield any immediate and direct advantages to the individual company, whereas progress in geophysical, gas-lift and cracking research does and will continue to yield such direct and immediate advantages. The

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author questions both of these contentions. There is serious question whether geophysics, gas-lift and cracking have not caused actual financial loss both to the industry as a whole and to the majority of the large companies. Temporary advantages gained in individual cases by any one or all of these new developments have been more than lost through the effect on the entire price structure of the industry. Any company engaged on a large scale in all the branches of the industry loses more money on all its operations through price depression than it makes in any one case through advantages derived from research of the type that adds to overproduction. To the question of immediate advantage to the individual company from research for new markets and products, the author refers Professor Johnson to the DuPont company and the Bakelite people for his answer.

The Market Price of Oil Securities

By J. Elmer Thomas,* Fort Worth, Tex., and M. D. Gould,† New York, N. Y.

(New York Meeting, February, 1929)

Until four years ago the market price of oil securities moved directly and immediately with the general list. This point was first developed by the senior author in 1924 while making a statistical study of the relative movement of oil securities and the general market. Plotting the monthly averages of 17 oils against 233 industrials disclosed the sur-

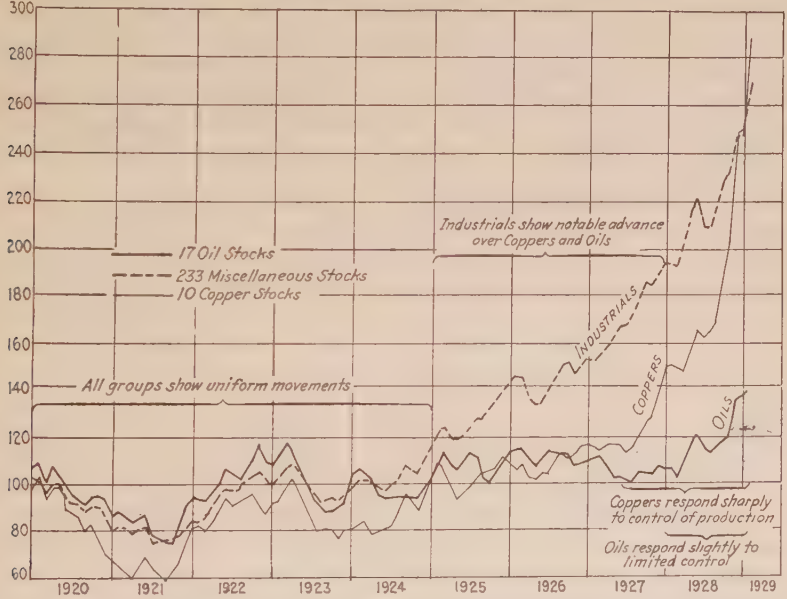

Fig. 1.—Relative market price of securities grouped as oil, copper and general.
Monthly averages referred to 1917–1921 average price as 100.

prising relationship shown in Fig. 1. The traditional vagaries of the oil business, the wide fluctuations in current supply and resulting abrupt changes in crude prices nevertheless produced no movements in the market price of oil securities as a group, which departed notably from the movements of the general market.

Obviously general business conditions did not always change when and as conditions in the oil industry changed; clearly the fluctuations of

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the few listed oil stocks did not dominate the movements of the many large, strong, diversified industrials. The conclusion is inescapable that buying and selling of oil securities was predicated upon public enthusiasm for speculation rather than upon recognition of a changing outlook for the oil industry.

In other words, if one had been convinced that the oil industry was about to exhibit great improvement, an investment in U. S. Steel, American Can, Woolworth and General Motors would produce about the same result as buying a well-selected list of oils. This seems ridiculous to the point of absurdity, but is clearly borne out by Fig. 1, which was named in 1924 "A Chart of Speculative Interest." Not only are the primary movements of major bull and bear markets shown to be identical for 17 oils and 233 industrials, but even the secondary movements of current trend exhibited the same relationship until January, 1925. Immediately thereafter a decided change was noted.

The so-called "Coolidge market" began in November, 1924, but there had been a pronounced rise for the preceding 15 months. The succeeding four years marks the period of greatest growth of public participation in stock market speculation, and the end is not yet. It would be novel to suggest that these "broader markets" become more selective markets for that reason, but the curve for oil stocks and the general list very definitely parted company four years ago, as did the curve for the copper group. Perhaps some similar cause can be found for these departures.

Failure of Oil Securities to Keep Pace with Industrials

Until one year ago oil securities maintained an approximate level while the general list doubled in value. During those three years the average of all industrials shows an almost uninterrupted advance, while the oil group fluctuated within narrow limits with a perceptible tendency to decline. During the good years of 1925 and 1926 levels were not notably different than during the poor year of 1927 and the inference is that in spite of the progressive improvement in the general list oil securities showed little response to the immediate outlook for the industry, good or bad.

The writers advance the tentative theory that the past four years witnessed the conversion of market prices from the basis of discounting near-by values to one of discounting values over an increasingly extended period. Whether or not the matter has been overdone is beside the point in this discussion. The fact remains that a striking advance was scored in the industrial list. The copper group did not participate until July, 1927, and the oils showed no tendency to follow until March, 1928. What is there common to both industries which could explain

this disparity? The answer may be found in overproduction and lack of control.

The decade since the war has witnessed the discovery of enormous deposits of copper ore just as it has disclosed extensive reserves of crude oil. It has also shown improvement in metallurgical technique comparable to the improvements in oil-refining methods. The lessened costs with increased production led the copper industry, as well as the oil industry, to build up unnecessary and burdensome inventories with increasing carrying costs and diminishing current prices. This condition progressed until profits were rare and deficits common.

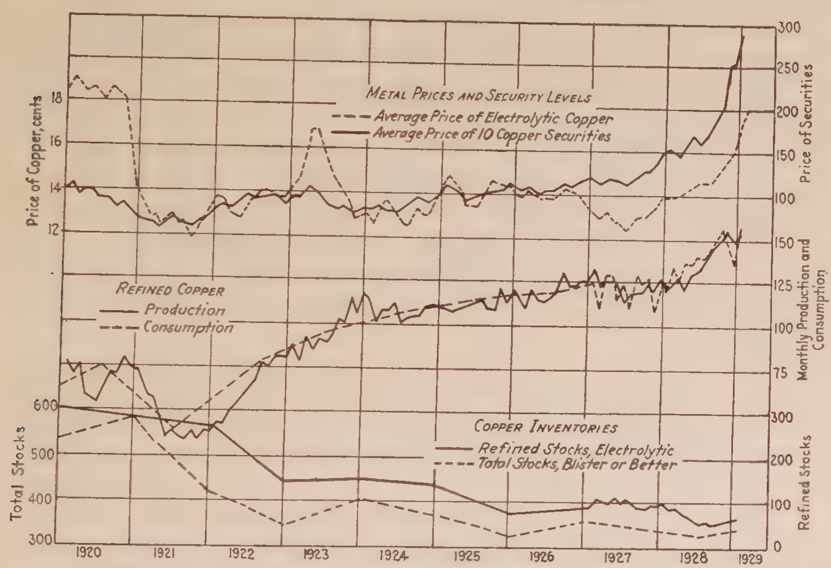

FIG. 2.—CHART OF THE COPPER INDUSTRY, 1920–1929.

Fig. 2 is a diagram of the copper industry for the past 9 years. The upper part of the chart shows the average price of 10 copper securities together with the prevailing price of electrolytic copper. Wide swings in the commodity price, ranging to 60 per cent. above its low in this period, produced great fluctuations in securities levels, ranging to 380 per cent. above their low in that period. The obvious inference is that a comparatively narrow swing in the quotations for the red metal makes a wide difference between substantial losses and notable profits, particularly with high-cost producers.

Conditions in the copper market seem to be such that neither the ore reserve in sight nor the supply of raw or "unfinished" copper in process of being refined is the significant index. The stocks of electrolytic, or "finished," copper appear to bear the most direct relationship to the

price fluctuations. Perhaps the relation of total refining capacity to total demand and the time and expense of constructing new capacity determines this point, but at any rate the curve at the bottom of the chart is for inventories of electrolytic copper in North and South America. It shows a notable decrease from 1920 to 1923, when there occurred a sharp but temporary upturn in the metal price. The reduction in stocks continued until 1927, when they increased slightly and the copper price again fell below 13 c. The persistent reduction in inventories during 1928 brought them to a new low point with a consequent advance in prices to 18 c. per lb. at the present time. The influence on security prices is equally evident.

The central part of the chart shows the relation between production and consumption. It indicates that the major force in the betterment of the copper industry was rapid increases in consumption rather than pronounced curtailment of production. In the past seven years production has increased nearly 300 per cent. but consumption, greatly aided by improved foreign demand, has kept ahead. The significant point is that copper could have been overproduced and overrefined, but was not. The ore reserves are probably greater than ever before and the stocks of crude copper are in fact somewhat above the average for the past 10 years; it is the available copper, the refined copper stocks, which were reduced.

Example of Copper Industry

When refined copper production was brought in step with consumption, copper securities promptly advanced to and beyond the levels previously attained by the general market. Whether or not the advances in copper prices and copper security levels have been carried too far is without the bounds of this discussion. The simple facts are recited for the purpose of permitting a comparison with the oil industry.

From the standpoint of industrial policy it may be of interest here to outline some of the leading differences between the successful methods employed by the copper industry as a whole and certain notably unsuccessful attempts to achieve similar results. We may cite, for purposes of comparison, the British effort with respect to rubber and the Cuban effort with respect to sugar.

The two latter had, in common with the copper and oil industries, a similar background of overproduction, unsound trade policies, excessive inventories, and prices which did not permit of a fair average margin of profit.

Both the rubber and sugar industries met this situation by a simple appeal to force in restricting production. Increasing efficiency in production, advertising and selling effort intended to increase consumption, statistical organization with a view to putting relevant information in the hands of producers for their voluntary cooperative action, all factors

which played an immense role in the success of the copper stabilization effort, played a minor role if any in the rubber and sugar schemes.

The two latter were in effect an attempt by organized producers to exert economic pressure upon the unorganized consumer, using their factor of organization as a weapon against the normal economic laws of supply and demand which for the time being were working out in a manner unsatisfactory to producers.

As the old truism has it, economic law cannot be successfully defied in the long run. A high price artificially maintained by restricting production involves a subsidy paid by the strong producer to the weaker producer, and is also a subsidy to actual or potential competition from

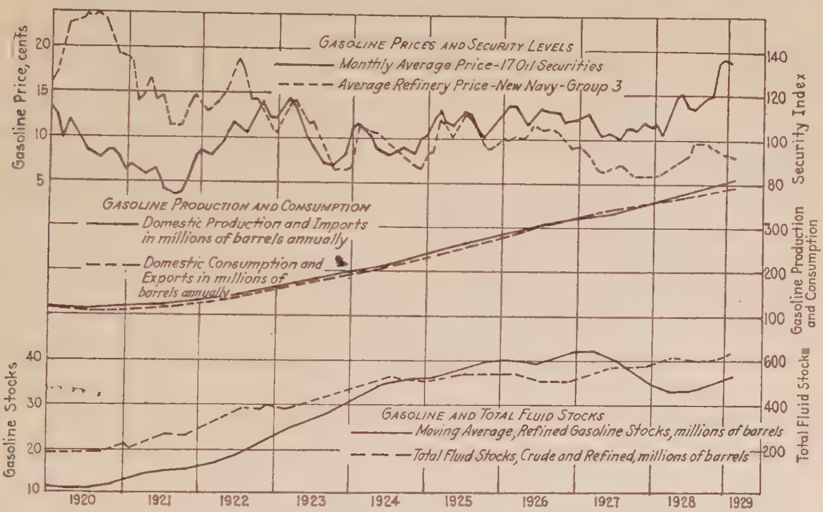

Fig. 3.—Chart of the petroleum industry, 1920–1929.

outside the restricted circle. Dutch-grown rubber and Javanese sugar broke the rubber and sugar pools.

The methods used by copper producers were in furtherance of, not in opposition to, normal economic trends. It has been demonstrated in other fields that great prosperity can come to an industry that is organized for large-scale economical production, intensive effort to expand consumption by broad-gage merchandising methods, and an attractively low price. The fact that these principles, plus a cooperative unit for the handling and preparation of statistics, were the base of the effort towards stabilization in the copper industry probably goes far to explain the success of the latter. It also provides certain signposts for the guidance of any future Moses who attempts to lead the oil industry into its Promised Land.

The difficulties experienced by the oil industry from 1924 to 1927 parallel the conditions in the copper industry—overproduction, too large

inventories and unsatisfactory price levels, as shown in Fig. 3. When the oil industry was called upon 15 years ago to convert itself from a kerosene to a gasoline basis it fulfilled its duty to the public by providing an adequate supply of motor fuel for the rapidly expanding automobile industry. With indefinite sources of supply the oil industry was accelerated to too great a speed and as a result accumulated burdensome inventories.

Overproduction in Oil Industry

During the past few years drilling has not only developed a potential production greatly above current requirements, but enormous reserves, far beyond amounts previously indicated, have been definitely proved. These operations, affecting a natural resource which has become a public necessity, should have been profitable, but the oil industry has been drowned in the flood of its own success. Aggressive drilling operations in proved areas, the prompt recovery of all disclosed reserves, are entirely unwarranted. Our large stocks on hand, our extensive shut-in production and our vast reserves now permit orderly and economical operations such as the copper industry exhibits.

The upper part of Fig. 3 shows the average price of 17 oil securities plotted against the average refinery price of gasoline. The prevailing quotation on crude oil is not a significant index to the oil business, since it represents merely an interdepartmental bookkeeping charge, considering the industry as a whole. It is rather the price of gasoline which produces income and therefore determines profits. Gasoline price movements show some similarity to crude price movements, but this need not always be the case, because an additional factor, the rate of manufacture of the refined product, is likewise a controlling influence. The industry seems never to have appreciated this sufficiently.

Proved undrilled reserves have now insured adequate sources of supply for years to come so that the maintenance of large storage stocks is no longer necessary. The existence of enormous shut-in potential production amounts in effect to an addition to crude inventories since empty tankage could be filled promptly by turning a gate valve at the well and on the pipe line. The actual stocks on hand are therefore much greater than the apparent storage, so far as crude is concerned.

The stocks on hand are subject to large seasonal variations, therefore the curve at the bottom of Fig. 3 is plotted as a moving average. In practice, the refineries manufacture and accumulate in the late winter and early spring a surplus of gasoline against the peak of demand in the summer and autumn. This permits their running plants steadily at or near their capacity and reduces their manufacturing costs. The annual consumption of gasoline in the aggregate can be forecast very closely and if it were not for the prevalent desire of most refiners and distributors

to overexpand their output at the expense of their competitors, there would be no occasion to overmanufacture gasoline.

The beneficial results of such restraint were clearly evident last summer. Gasoline had been moving at an absurdly low price and when the current consumptive demand approached the current available supply, price quotations indicated more closely the proper consumer value of the commodity, as shown at the top of the chart. Resultant improvement in earnings was quickly reflected in oil-security price levels, but profits so greatly accelerated both the rate of crude oil production and gasoline manufacture that the price levels of those commodities declined and security price levels subsequently followed.

In the central part of Fig. 3 have been plotted the relative production and consumption of gasoline as annual averages. This is not the balance which the oil industry usually studies; the customary chart depicts the production of crude and consumption of crude and refined as reflected by changes in total fluid stocks. However, if the comparison with copper is valid, it would seem to be rather the supply of available, marketable gasoline which is significant. Including cracking stills, the refining capacity of the country is in excess of its current consumptive demand and it is possible, through greater elasticity, to step up the output of oil refineries more promptly than the copper industry could meet a similar situation. Nevertheless a realization of the benefits of similar control should permit the oil industry to take similar action.

If crude should be produced only in sufficient amount to meet the refining demand, if gasoline should be manufactured only in sufficient amount to meet the consumptive demand, or even slightly below it to reduce inventories, and if products should be marketed in each area only by such districts as can most efficiently supply the demand in each area, oil can once more sell at its proper competitive commodity value; but even if crude is overproduced only restraint in refining can work a great betterment, as was exemplified last summer.

A geographical allocation, voluntary or imposed, of consumptive demand in each area to those districts best able to supply such demand, would save to the industry for profits large sums now wasted in unnecessary and uneconomic freight hauls. Reducing the distribution effort would make for a "sellers' market," would diminish the merchandizing efforts now being wasted and further increase marketing profits. Salesmanship never sold an extra gallon of gasoline; it merely supplied that consumptive demand from one pump instead of another and in the aggregate the industry, not the public, paid for that effort.

Confining refining schedules to a point just below the estimated demand would prevent the refiners from expending the manufacturing cost on unneeded inventories of gasoline which may, and frequently do, become distress stocks dumped on an unwilling market at any price.

Such a determined refinery program would promptly limit the apparent demand, a false one, for this oversupplied and overpurchased crude. Thus inventory losses which the industry sustains on crude price declines could be minimized.

The crude producers are not solely to blame for overproduction. The buyer's demand for crude has nearly always been well in excess of the consumers' demand for gasoline. The reason for this must be found in the naïve desire of most pipe lines and refineries to increase their business at the expense of their competitors. With an average annual increase of 8 per cent. in gasoline consumption the average refiner has an annual ambition to increase his output perhaps 20 per cent. In the aggregate it cannot be done. Hoping to lower refining costs and increase profits the frequent result has been to lower selling prices and decrease profits.

Restraint in refining operations would go far towards removing this false demand for excess production. The lack of a market would then give producers the choice of leaving their supply in its natural underground storage or of erecting tankage. The workings of a simple, fundamental economic law could soon accomplish more than proration committees, conservation boards, or legislative panaceas. And if the remedy were sound the relief could be permanent.

Oil Securities Should Reflect Improved Conditions

Oil security prices should respond as definitely as did copper security prices to equally favorable conditions in operations and earnings. Fig. 1 shows that a pronounced group movement in the oils started about a year ago when curtailment in producing and restraint in refining operations were evident. The control was partial and voluntary and was diminished late in the year, but not before greatly improved earnings were assured. When the unfortunate results of this relaxation—overproduction, lower prices, and reduced earnings—became apparent, security prices tumbled from 10 to 30 per cent. in some cases. Reinstating the conditions that permitted the improvement last year, and effecting an arrangement to assure their permanence, should bring good times back to the oil industry for a prolonged period.

If our theory of the basis of stock market prices as based on the discounting of long-term earning power is correct, there would seem to be no *a priori* reason why oil stocks, with earning power assured as above, should not sell at a ratio to true net earnings comparable to that of other security groups which have long ago left behind them the traditional basis of capitalization of earnings at 10 per cent. In other words, not only would the earning base be higher, but the multiplier of earnings representing market valuation would also be higher. The foundation would be laid for an advance in oil stock prices which would be repre-

sented by a curve more nearly parallel to that of the general market and of copper stocks.

DISCUSSION

E. R. Lilley,* New York, N. Y.—Mr. Thomas has drawn a very definite comparison between the oil business and the copper business. At the present time the price of copper is eighteen cents. The copper business looks like a far better business to invest in than the oil business. I think, however, we should recognize that copper is at the top of one of its cycles. The copper industry has had its periods of low prices and depressions just as the oil business has, and I think we will find such a period returning again in a very short time.

Previous to the war the copper industry was able to pull itself out of or ward off periods of depressions, by means of associations and cartels, to some extent. However, none were wholly successful. At the close of the war the refiners and marketers of copper organized an export association in the United States that was supposed to control the exportation of copper and thus indirectly to improve the general situation. It failed to accomplish its purpose. At the present time we have a similar organization operating under the Webb Act. It is succeeding temporarily. There are a large number of potential copper properties. However, there are only a limited number of properties now capable of producing. The investment in every piece of property runs into millions of dollars, not a few hundred or a few thousand as in the single well. Secondly, the organization for changing copper ore into metallic copper, that is, blister copper, is a costly organization. Lastly, the number of electrolytic refineries for copper can be named or listed on the fingers of two hands. There is a close grouping with only a few in control. At the present time, also, practically all of the copper mines of any importance, with the exception of one great mine in the Katanga section, are under the control of a few concerns operating from local centers, either New York or Boston. There is a vast difference in the situation in the copper industry and in the situation in the oil industry, yet in the copper industry the cycle has already started the other way. New mines are being floated and that excess of capital that Mr. Pogue speaks about is being brought into the copper industry. It takes longer, but the cycle is the same.

May I point out one thing in addition? Refiners have a means of controlling operations in the United States. They can control them, I think, for a year, maybe two years, but if the price of crude oil is kept down, there is great inducement for every producer to go into the refining business. Go through the history of the oil companies for the last few years, even including all of the period since the beginning of the development of the industry. Every time that gasoline prices are maintained while crude oil prices go down, skimming plants become prominent. West Texas is the last example. Add their gasoline supply to the amount of available gasoline and it will break the market, unless the crude production situation is remedied.

* Associate Professor of Geology, New York University.

Chapter VI. Petroleum Engineering Education*

Is the Petroleum Industry Underengineered and, if so, to What Extent?

Introduction by L. C. Uren,† Chairman

Some of us have been impressed with the need for a better understanding of the future place of the engineer in the petroleum industry. In academic work we are continually asked to advise students as to the opportunities in different directions, to guide them in their selection of professions, and it would be extremely helpful to those in academic lines of work to have the opinion of engineers from the industry relative to the need for petroleum engineers.

Is the industry going to require a continually growing number of engineers in the future years, or have we perhaps reached equilibrium in that regard?

In anticipation of this meeting, I undertook to canvass opinion among a number of engineers of my acquaintance and I have been rather astonished to learn that the expenditure on engineering salaries in the producing branch of the oil industry is extremely low. I have figures from eight or 10 of the larger oil companies and it seems to be a fair statement on the basis of these figures to say that the average American oil company is devoting less than 2 per cent. of its gross expenditures in oil production to the payment of engineering salaries.

A few examples will be of interest. I shall not mention names of individual companies, but one large Mid-Continent company is spending slightly less than 1 per cent. of its gross expenditure—that is, less than 1 per cent. of the total expenditure in the producing department—on engineering salaries and about as much on engineering research, which might properly be regarded as a phase of its engineering work. Another Mid-Continent company is spending about 1¼ per cent. on engineering salaries. A large California company is spending about 1½ per cent. The largest figure that has come to my attention is that of an important Rocky Mountain and Mid-Continent company that is spending a little more than 6 per cent., but that is apparently an extreme case.

The petroleum producing industry is a highly technical business in these days. It is spending in excess of $500,000,000 annually in new

*A session of the Annual Meeting, February, 1929, was devoted to a general discussion on Petroleum Engineering Education topics as reported in this chapter.

† Professor of Petroleum Engineering, University of California, Berkeley, Calif.

development work and in the operation of properties for oil production and it would appear to many of us that every dollar of this expenditure should be regulated and controlled by engineers. Other engineering industries are spending much higher percentages than those I have just indicated. The building industries, for example, commonly allow from 4 to 6 per cent. of their total expenditure for engineering design and supervision.

I have similar figures from a number of mining companies, copper-mining companies particularly, in which the figure runs from 4 to 6 per cent., and here we have the petroleum producing industry, more technical perhaps than either of these other fields, spending less than 2 per cent.

The demands on the engineering profession in the field of petroleum production appear to be increasing. We are ever venturing into more technical methods, the gas-lift, repressuring of properties, secondary methods of recovery in general, and water-flooding; all demand a much higher technique than the industry has made use of in past years.

Many operations on the oil property involve a high order of engineering skill. Design and construction, and operation of pipe lines for oil and gas transmission, and the problems of dehydration and storage are all highly technical matters in these days. It would seem that the oil industry has need of a greater number of engineers to properly develop and control these processes. Deep drilling, with increased weight of equipment, and many other problems that have arisen in the development of drilling methods, would seem to demand a higher order of engineering than we have had in years past.

The industry is turning to its engineers for administrative recruits. Some of the most responsible positions in the administrative field are now recognized as properly open to engineers. Field superintendents, managers of oil companies, directors, and even presidents of oil companies are in these days being recruited from the engineering field. It would seem that further transfers of engineering personnel into these positions might leave greater opportunities in the future for new men in the industry from the general engineering ranks.

These are but a few thoughts that have come to me in this matter and they all seem to point to the conclusion that the petroleum industry of today is really underengineered, that oil companies might find it profitable to add materially to the number of engineers in their employ. Presumably they employ engineers because it is profitable for them to do so. If an oil company finds it profitable to employ 10 engineers, would it not possibly be more profitable to employ 20, and if 20 is better than 10, perhaps 30 is better still.

Obviously there is a balance there beyond which it becomes uneconomical to employ additional personnel, but I have a feeling that we

have not nearly reached this economic balance at the present time. We have the habit of going along content with the present situation, with the existing order of things, without really looking into the actual needs, and I believe that if a real study of this situation were made, it would be found that the oil industry today is underengineered.

DISCUSSION

E. L. Estabrook,* New York, N. Y.—I am interested in the differences of viewpoint which this discussion brings out. When Mr. Uren asked me the question; are the oil companies overengineered?[1], my thoughts took quite a different track from his. He has been talking about the engineering establishment of a company while I did not think of it in those terms at all. The point to my thoughts was that in our companies there are from 15 to 25 well paid executive positions which would be open to engineers were the men available. A great deal of money is being spent inefficiently by the petroleum industry because the men in charge of the work do not have engineering experience or do not know how to use engineers.

Engineering Education not Limited to Staff Positions

Engineering education is a broad subject which must be subdivided if we are to understand each other. The petroleum engineer to whom my remarks apply particularly, needs more purely engineering training than does the geophysicist or the geologist and probably even more than does the mining engineer. In our company the geological department determines the casing point and the depth of the hole and the production engineer takes over thereafter deciding on casing sizes, perforations, where the liners are to be set and the other questions connected with the production of oil. This production of oil calls into play certain phases of education that have not been called for in mining education and requires a somewhat different preparation. The mining engineer deals primarily with tangible physical properties—volumes of rock to be broken and moved, shafts to be sunk and drifts to be driven. Young men start in the mining business either as laborers, assayers or surveyors. The young oil production engineer has different problems and will enter his business in a different way. He will not break in as a chemist and probably not as a surveyor but must start either as a geologist or as a production man or driller in the field. The latter method is much to be preferred for it not only assures a thorough understanding of the practical operation of an oil field but makes it unnecessary for him to acquire an elaborate geological education. Many of our oil fields show no surface geology and since the petroleum engineer is not usually called upon for any study of the formations except those in which the oil occurs, he does not need much more than the fundamentals of geology. His problems particularly involve factors of pressure, temperature and gas ratios. They are not the tangible physical problems of the mining engineer but are theoretical in their nature. Proper preparation for this type of work requires training in physics and mechanics. Probably the student needs analytical geometry and other similar subjects which will train him in thinking objectively, if he is to solve these problems involving liquids and gases in a reservoir several thousand feet below the surface.

The other side of the petroleum engineer's work is purely engineering. He will deal with power plants, the building of structures, electrical problems, mechanical, architectural and civil government problems. Aside from this one phase of dealing with gas and oil in their theoretic relationships below ground, he is purely an operating

* Petroleum Engineer, Pan American Petroleum & Transport Co.

[1] In the program of the annual meeting the question was changed to read: "Is the Petroleum Industry Overengineered and, if so, to What Extent?

engineer. For production engineers we need men who are primarily engineers and particularly men who have a good theoretic knowledge of physics and mechanics.

H. C. George,* Norman, Okla.—As Mr. Estabrook has said, sometimes when we think of engineering, we think of the men in the engineering department of any corporation who are known as staff engineers, but where we need one man as a staff engineer, we probably need 10, 15 or 20 men with engineering training in the various branches of these industries, who are not ordinarily classed as engineers, yet they are engineers, and it is along the line indicated by Dr. George Otis Smith,[2] that is, that in any industry, even extending as far as politics and government, what we need is a background of engineering training. Following out that line of thought, what we need in the petroleum industry is a group of men who ultimately are engineers, if not by academic training at least by tendency or experience.

If, for instance, in our educational problems we were just training engineers to fill staff positions in our various mining and oil companies, it seems to me that most of us educators had better quit, because the schools without any great effort could meet that demand, but I think that if you should ask anyone in an oil or mining company who has a knowledge of engineering, he would say that engineering is what we need in all of our departments for efficient and proper interpretation of results, and for making an adequate and proper profit on our operations.

Training in Use of English Language

J. R. Suman,† Houston, Tex.—When I investigated how much money we were spending on engineering, I thought we were somewhat overengineered, but I was very much interested in what Mr. Estabrook said. I think he has outlined the qualifications for the subjects in which we would like to have engineers trained.

I might mention also the importance of training an engineer in the use of the English language. I think that is very important. I happened to graduate in a class of mining engineers and I will say without reservation that the most brilliant man in that class of mining engineering could not get out and write a report on a mining property that would be intelligible to the company for which he was working, and that is a great handicap to a young engineer.

Company Interest in the Young Oil Field Engineer

When these young engineers come to us, we assume that they have been trained along some such line as Mr. Estabrook mentioned. We should like to have them trained along those lines, and we are further interested in the engineer from two standpoints: (1) as an investment to return us dividends and (2) in his success as an engineer. We believe there are many factors besides his college education that have to do with his success and we immediately start to perfect the human side.

We get the men to Houston and give them a talk something like this: "Forget that you have ever been to college. You are going out to meet people and you are going to roughneck on the derrick floor, maybe for a year or two; and all it takes on that derrick floor is a number 10 shoe, a number 5 hat, a strong back, and a weak mind."

We observe these boys very closely. An engineer will never be a success unless he can get along with people and that is particularly true in Texas.

We watch these boys closely and we like to keep them on the derrick floors longer than we have been, but it so happens that we have been moving them up rather quickly

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* Director, School of Petroleum Engineering, University of Oklahoma.

† Director, Production Department, Humble Oil & Refining Co.

[2] G. O. Smith: Engineering Standards for Society. (Address at A. I. M. E. annual dinner, 1929.) *Min. & Met.* (1929) **10**, 113.

due to the demand for petroleum engineers. I think the future of the petroleum engineers as to securing positions is very good. We should like to have a larger percentage of our drilling staff petroleum engineers. The Gulf Company in Texas has six or seven graduate engineers who are drilling on the deep rotary wells and performing well and I think you could help us a good deal in the universities if you stressed to students the future of drilling. A man with a medium physique has as good a chance as anyone else; when he gets on the derrick floor, he is not handicapped if he will forget that he has been to college.

Let us consider the dignity of the profession of drilling. I think it is very commendable as something for a petroleum engineer to look forward to. We pay these men $300 a month and they have an investment of $100,000 in their hands while they have charge of the rig, and with the $70,000 or $80,000 worth of equipment they are using it is a responsibility that well merits the attention of an engineer. Our idea is that we would draft from this group of experienced engineering drillers, our staff for carrying on our work, and when we come to draft them, the qualifications would be about 20 per cent. as to engineering training, about 30 per cent. as to ability as a driller, and about 50 per cent. as to ability to get along with people.

Petroleum Industry is Underengineered

J. B. Umpleby,* Oklahoma City, Okla.—When you sent the questionnaire asking if the petroleum industry was underengineered, my answer was that it is. It is in the nature of the case that it must be. In the mining industry we have had, ever since I was a student, a threefold division of technical work; a mining geologist, a mining engineer, and a metallurgist.

In the petroleum industry for a great many years we have had only two of these fields represented. We have had the petroleum geologist, representing the finding group and the refinery technologist representing the reduction group, but we have had no group of technical men representing that great and most important middle field, getting the oil out of the ground at minimum cost.

I think it was in 1924 that John Suman prepared the first handbook of petroleum engineering. It was a year or two later when the chairman of this session, Professor Uren, prepared the first textbook. When I was teaching in California, as recently as 1916, Professor Uren was a graduate student, searching through the oil and technical journals trying to get material together for what I believe was the first course in petroleum production engineering offered by any university. At the time this committee made its survey in 1926 there were only six schools teaching production engineering. Viewed from this angle, it is obvious that if the petroleum industry has a fundamental place for petroleum engineers, it is undermanned.

Considered from the standpoint of the needs of the industry, I believe that the time is coming when the entire production end, down to the farm bosses in charge of the more important leases will be technically trained men.

I think most of the administrative positions in the oil companies which have to do primarily with production should be in the hands of engineers.

This cannot all happen at once because it takes experience and aptitude outside of technical training to hold an administrative position in such an active and changing organization as an oil company, so here again the conclusion follows that the oil industry is undermanned from the engineering standpoint. Many other considerations lead to the same conclusion. I believe the study of petroleum engineering education is a most constructive piece of work and that this Institute is making a real contribution in carrying it on. Many schools are contemplating putting in petroleum engineering departments and if we can help in some small way in formulat-

* President, Goldelline Oil Corpn.

ing what should go into the curriculum, the kind of training men ought to have, etc., it is well worth while.

There is one other thought based on considerable experience with students. Many of us come in contact with student groups and in our talks before them I believe we should emphasize the fact that the university only offers a groundwork for further training. When they get out of school, they should count on two or three years of apprenticeship in the field. The attitude of most of the companies, as Mr. Suman suggested, is to put young graduates through such an apprenticeship, and graduates should expect this and consider it a postgraduate course for three or four years. In this way there will be developed a group of raw material from which the industry will automatically take its men for many important positions. The industry is underengineered at present and will be for some time.

Engineering Material as Source for Future Executives

R. H. Johnson,* Pittsburgh, Pa.—Taking the question literally, it seems to me there can be no doubt that the previous speakers are all correct in saying that the petroleum industry is underengineered. I have in mind that the characteristic of the engineer is partly an attitude and a mode of attack as well as a specific knowledge; that is, he is more analytic, more quantitative, and he is more objective, if his education has been a proper one.

Now these are the traits especially desired in the executives and I agree particularly with Mr. Estabrook that it is desirable that the companies should get a sufficiently large amount of this class of material among the younger men so that they may select from it as the future needs for executives arise. This is the more important because we have a backward industry as compared with some of the others. It started suddenly as late as 1859, and originally was made up largely of lumbermen, salt well drillers and the like. It has always tended to draw in to itself a great many of the local bankers, real estate men, etc., as the various fields developed.

From the nature of its history, it seems to me to have an extraordinarily large percentage of nontrained men, and I think it is time for the industry to take stock of that situation and try to do as the company men who are here have said, get quite a large number of these young men from whom they can select.

I think we should perhaps stress the selective side a little more than the previous speakers have done. All of these graduates are not going to be material for the executive positions. It is necessary to have a number, from among whom by a selective process, the desirable ones for promotion can be developed. A number of them are going to be dropped by the way, no matter how good the educational process, by reason of their natural limitations; they cannot meet the high demands on the successful executives.

We may take this question in a different sense, from the practical standpoint of job-getting. We have been thinking of it from our standpoint, let us look at it from the student's for a moment—they come to us and say, What are the opportunities in the position?

Student Body Responsive to Company Demand for Engineers

I have come to feel that the student body is more responsive to the relative demand than we suppose. As I can see the number of men who go into refining and production and engineering or its various subdivisions, there is a rather nice adjustment and when for a certain time the demand comes from a certain field, the students way back in the freshman and sophomore years respond to it, so I think the industry can

* Professor of Oil and Gas Production, University of Pittsburgh.

have as many men as it wants and the response will be quicker than they suppose when there is a real demand made on the colleges for any particular kind of material. The students respond very quickly.

At the session on Engineering Education[3] it was assumed by some that scholarships would have to be developed, or some device of that sort, to build up material. In my opinion that is not at all true. I believe the material can be had when the companies appeal sufficiently early. The demand will quickly develop its supply.

For my third point I wish to diverge a bit from the central question to make a strong dissent to the position of one of the speakers at the session cited above. He deplored the fact that the companies come to the colleges and wish to contract with its selected students early, and he said that we ought to have a general agreement among the companies and colleges by which the companies would not do that, but would all pick their men along about graduation time on some sort of a systematic distributional scheme.

I believe that this is fundamentally wrong, partly because it does not give the student this measure of demand that he needs to know in choosing the particular line that he is going to take, which he readily gets by seeing how early the companies come and how much they are paying and how many they take for the several lines. Thus we lose the advantage of a barometer which is so useful to him on the one hand, and, on the other hand, we would lose a policy which seems to me to have been the best that I have found in this matter of personnel.

I believe that the company does best which comes to the college in the spring, sufficiently early to get the men when they are in the second semester of the junior year. Then we have a sufficiently good line to act as a guide in the selection of quality, and the man is then taken and given a preliminary tryout in the summer.

That has this advantage: It permits us to get the proper experience for these men, which is very important. We are extremely loath to let men go out at the end of the senior year without experience. It is sometimes assumed that the colleges are at fault in that. From the faculty end, at least, we are all very eager to give them that.

It helps to get the men placed, and the company is able to show its particular problems; its situation geographically or otherwise may be somewhat different from the general one, so that the young man gets his opportunity to know more of the particular needs that he should fit himself towards and be motivated with respect to those particular needs, which is rather effective, when he sees its importance.

Selection of Young Engineer Material Reduces Turnover

But from a personnel standpoint, there is a further advantage in that the company has its chance in this way of picking over that material and reducing its later turnover. They can select the better material and that better material will have a very much reduced turnover and very much greater satisfaction.

My feeling is that there is enough difference between graduates so that no company can consider that all of the graduates are a substantially standardized product and I would recommend any company to take twice as many men on trial in the summer as they really intend to take later, if they can get them, in order to have this opportunity of selection.

Few Students Majoring in Petroleum Engineering

L. C. Uren.—I think some of us have been rather astonished at the figures published in the last issue of *Mining and Metallurgy*,[4] in finding that of 65,520 engineering

[3] Annual Meeting, A. I. M. E., Feb. 18, 1929.
[4] Feb., 1929, page 73.

students in the schools at this time, only 372 are majoring in petroleum engineering. Three hundred and seventy-two seems like a very small number in meeting the prospective demands of an industry such as ours. To be sure, there are others in other classifications, geological particularly, and perhaps in the general branches of engineering, who contemplate entering the petroleum industry, but I think we have in this 372 the best equipped group for the purposes of the oil-producing industry in general, and the figure seems unduly small in view of the obvious needs of the industry.

C. D. Watson,* Tulsa, Okla. (written discussion).—I believe that the development within the industry for the past two or three years, in so far as engineering is concerned, has crystallized the idea that the industry really needs trained and technical men. By "trained," I have in mind men who have had a thorough engineer's education, together with a considerable amount of practical experience in the field which would fit them to coordinate mentally the theoretical with the practical ideas.

Recently there seems to have been a rather heavy demand for petroleum engineers, and it has been the experience of most companies employing this particular type of men, that practically all of the technical men who have had considerable practical field experience are already employed, and they do not seem to want to trust the judgment of the younger men who are just out of school and who have finished the more or less recently installed petroleum engineering curriculum. In other words, the engineers have been able to sell the idea of engineering to the petroleum industry only at such a recent time, and the idea has been taken with such rapidity that there does not seem to be available the type of qualified engineers that are required, and it seems to me that there will probably be a transition period lasting from five to 10 years or more, before the technical men can be firmly established within the industry.

It will be recalled that the mining industry went through the same period of transition, until at the present time practically every superintendent or manager of a mining company is a technical man. His experience, however, in addition to his schooling, must have been obtained through the different departments of the industry. It seems that it will be necessary for the young petroleum engineers to get jobs as roustabouts, roughnecks, and tool dressers, and then if they are able to develop the capabilities that are necessary, they most certainly can advance into positions of authority where their technical training will be a real asset to their employer and the industry. Naturally, as soon as a number of these technically trained men have been able to advance into key positions, they will undoubtedly appreciate the potential value of technically trained men in the organization, and while it is necessary that petroleum engineers as such be of high calibre and more or less specialized in production problems, nevertheless, where the men who are actually in charge of producing the oil are also technical men, a much better coordination can certainly be had. I do not mean to infer that cooperation between the engineers and the field forces is not gaining ground now, but that for greater efficiency, it will probably be necessary to have a greater cooperation in the future.

Field Experience as Prerequisite for Engineering Department Position

Speaking of these young engineers just out of school, it is generally their desire to get a position in the engineering department rather than withstand the heavy work that is necessary to gain the practical experience in the actual producing of the oil, and in view of this trend, a number of the larger companies are requiring that young production or petroleum engineers, have at least two years' experience in actual production work before they are taken into the production engineering department,

* Carter Oil Co.

or division. This process is intended to eliminate those who are not qualified and to be better able to judge those who have special qualifications for different positions in the organization.

There has already been so much said and written about the need for technically trained men in the producing end of the business, that it is really difficult to bring out any new line of thought, and it is certain that with the sympathy which the leaders of the industry have towards technical methods, the engineer has an opportunity, and if and when the industry, or at least the major operating companies, are manned in their various units with at least 25 per cent. technical men, then the capable young engineer can look forward to a singular opportunity in this industry.

Few Technically Trained Men in Managerial Positions

E. G. Gaylord,* San Francisco, Calif. (written discussion).—In general I believe that the petroleum industry is underengineered, both with regard to the actual engineering problems arising in the industry, and what is probably even more important, that the industry has comparatively few technically trained men in the managerial or executive branch. In this connection, I believe that the petroleum engineering schools should prepare and advise more men to go into field work in petroleum production with the idea of working up to superintendents' and managers' positions from the practical side of the work. The industry is also underengineered in the operating staff and more young engineers should be encouraged to take the so-called manual labor jobs rather than "white collar" jobs.

F. E. Wood,† Casper, Wyo. (written discussion).—It is my impression that the petroleum industry is greatly underengineered. It does not require a great deal of analysis from one thoroughly acquainted with oil operations to understand our meager knowledge of the flow of oil and gas through sands, flow of oil and gas mixtures from the wells through tubing or casing, the proper type of control to result in the greatest efficiency from the natural energy in the gas produced with the oil, the proper type of well pumps for producing oil, lack of control of tools in drilling wells, etc. Some day these problems must be put on a scientific basis and it is the engineer alone who can do this type of work.

Production Engineering Knowledge only Partly Utilized

F. W. Lake,‡ Brea, Calif. (written discussion).—Were the engineering knowledge now available to the development and production section of the oil industry properly utilized in common field practice, I doubt if this branch of the industry could be considered underengineered. However, conditions existing in most operating companies are such that possibly but 25 to 50 per cent. of the engineering knowledge available is actually utilized either because of the relatively insignificant position of the engineer, as to authority, in the operating units, or because of the lack of practical oil field training on the part of the engineer.

Of all of the engineers engaged in the development and production section of the industry, there is but a small percentage who are fully qualified both by training and experience and of this small percentage, there are still fewer numbers who are in such positions of authority that their training and experience can be practically utilized.

* Standard Oil Co. of California.

† Petroleum Engineer, Midwest Refining Co.

‡ Superintendent of Production, Union Oil Co. of California.

The Fear of Being Overlooked

R. H. Johnson.—May I add one word in discussion of what Mr. Suman said? I think that boys should realize the situation that Mr. Suman describes, when they go on the derrick floor, or to the rather simple mechanical work, relative to their eventual ambitions. If they knew that they were being watched and selected, they would feel very much more satisfied. The trouble, for which the boys are sometimes blamed, I think, is not altogether their fault. They have a fear, when they are put into the simple jobs, that they may be overlooked and forgotten. It is a not an unnatural fear, and if something can be done by the company to allay that fear, some tangible evidence that they are actually being watched and that they will get their promotion at the right time, we will not have this thing for which they have been criticized, of hankering for "white collar" jobs, to the extent that they have.

Mr. Suman referred to the fact that they sometimes did not realize they were being watched as much as they were. Unfortunately that is very frequently true. I have talked to them and I know that it is not the dissatisfaction with the hardships of the work so much as a fear, which is sometimes a legitimate one, that they are not getting attention.

Being watched to the proper extent means a proper rating that will come to the officials. Sometimes they are under the observation of a man above them who is not capable or is unwilling, somehow or other, to rate them adequately, so this rating will go to the responsible officials with whom lies the question of their transfer or promotion. The improvement of the personnel machinery and personnel contact would go far to make the young undergraduate better contented and reduce the turnover.

L. C. Uren.—I think that is a very good point and one phase of the work that is not being taken care of adequately either by the schools or by the industry at the present time.

K. C. Heald,* Pittsburgh, Pa.—I am not sure I am entirely in sympathy with the point Dr. Johnson just raised. I think our young engineers are watched very carefully and, on the other hand, I do not think the oil companies are particularly interested in making them feel too contented. We have found some of them have had a tendency to be rather too smug—I call it "smug" rather than "discontented."

I think most of the companies that have engineers have men who are interested in those engineers. They hire them in the hope that they will work out to be good company men and we are not going to overlook any opportunities along that line.

The Gypsy Oil Co. starts most of its young engineers as roustabouts. It makes them no promises. They are told that if they make good they will go ahead, but they are not told that they will go ahead regardless of performance. That is because some of them ought to be roustabouts and as far as the Gypsy is concerned, they always will be roustabouts. But if a man really has the stuff in him, if he shows that he is ambitious and intelligent, I do not think there is much danger of the young engineer being overlooked.

We have had a fairly heavy turnover among our young engineers. Young engineers get dissatisfied and leave us, but I do not think we have ever lost a man who was really willing to pitch in and get his shirt dirty.

I do not think the petroleum industry is undermanned today as far as young engineers are concerned, if we have in mind only today's needs. If we could throw into the field 2000 more engineers per month, it would not help us a great deal. That is because the petroleum engineers are immature, because of the necessity of having to take young men, and because of having unseasoned timber. We have not, as in mining engineering, civil engineering and electrical engineering, men with a back-

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* Staff Geologist, The Gulf Oil Companies.

ground, and we realize more and more every day that it does take experience. There is a dearth of men with real background to put into engineering jobs in the petroleum field.

I do feel we are undermanned when we are looking to the future. We do want to fill many places with men with engineering training. Every time I attend one of our zone meetings, where our engineers and tool pushers, and superintendents, discuss their problems, I am impressed with the fact that those men are eager and capable and willing to learn, but they are handicapped until they acquire a background of theory to help them go ahead and solve their problems.

In connection with engineering training in schools, I was much impressed with a statement made by President Lowell, of Harvard, who apparently does not believe in engineering training at all. He told a group of men here in New York, "We are not in the least interested in training men and giving you men who are capable of solving problems. We do not feel that is our function. That is not the function of the university. The thing that you need and we want to give you, is men who can tell you what the problems are," and that is what we need in our engineers and I think that you, Professor Uren, and Dr. Johnson, and Professor Bonine, could bear down hard on this matter of being able to analyze a problem. That is the type of man who is needed for executive engineering positions and we get very few of them among our engineering men.

To What Extent Should the Engineering Schools Attempt to Train Research Specialists for the Industry?

INTRODUCTION BY L. C. UREN, CHAIRMAN

The training of skilled research workers apparently demands something more than the four years of academic preparation that the average engineering student receives, perhaps a period of graduate work, possibly something akin to what is commonly regarded as necessary for the Ph. D. degree. Should the engineering schools now seeking to prepare students for the oil-producing industry provide additional research training beyond what is now provided? Should they possibly lengthen their period of undergraduate preparation in order to include this additional training? Is the industry content with the plan which it is now forced to follow of bringing research personnel from outside of the industry to solve these problems, personnel having but a limited knowledge of the oil business and its ways, or would it be better perhaps to superimpose on the petroleum engineer's training, at least for some of them inclined this way, a period of research training that would develop a reservoir of material, of personnel available to the oil industry for this new work?

DISCUSSION

C. D. WATSON.—There is a great need for research work on hundreds of problems in the producing end of the business; however it is difficult to decide to what extent and upon what problems research work should be done, all of which possibly reverts back to the question: "What is petroleum engineering research"? Is it a development of theories or hypotheses that cannot be put into immediate practical use, or is it a development of theories or problems that can be developed economically?

There have been one or two attempts by larger companies to develop a thoroughly rounded research staff, and in one instance at least, this has had a temporary setback, probably because the work was carried too far beyond the point upon which the results of the research could be immediately capitalized, or possibly because the management of the companies could not be sold to an extensive experimental campaign. On the other hand, there has been considerable conservative research work done by practically all of the major companies along the line of chemical and physical engineering, much of which has proved the value of research.

Undoubtedly in the near future it will be advisable for the universities that have specialized in engineering courses to devote some time to these special problems requiring solution by research, and I have no doubt that a symposium on this one subject would develop a considerable number of problems that await solution and upon which a line of procedure could be developed into a definitely outlined course. Naturally, as research work is developed within the industry and after it becomes more depended upon to solve these apparently intangible problems, there will be an increased demand for research engineers.

Selection of Research Specialists for Special Problems

F. W. Lake.—The most feasible method seems to be to select qualified research specialists, either pure physicists, chemists, mathematicians, or metallurgists, as the case may be, for each special problem. In this way, the engineering schools need not train research specialists who would be employed only in the oil industry, but the industry could make use of the specialists in any particular problem. This plan seems more feasible than to attempt to obtain or train research specialists familiar with all branches of the production division and who will have had sufficient training and experience to be valuable.

F. E. Wood.—The schools at this time should merely attempt to train research specialists in the fundamental principles of science. Such students should learn the work of the geologist or production engineer in the engineering offices of the oil companies. It is my belief that the companies are far ahead of the schools at this time in their knowledge of geology and production engineering, for it appears that the schools are endeavoring to learn as much as possible regarding company work and are using the information so acquired in their classes. Unless the engineering schools are in a position to develop technique in advance of company work, it seems that a thorough grounding of a student in science is the most valuable equipment that the present-day engineering school can give to a prospective research specialist. The day may not be far off when the schools will be ahead of the industry and they can then go farther in training research specialists.

E. G. Gaylord.—Petroleum engineering schools should not attempt to develop research petroleum engineers. Research in petroleum engineering methods is best carried on by a staff of specialists, chemists, physicists, mechanical and electrical engineers under the direction of a petroleum engineer of considerable field experience who can direct the work of the pure scientists and younger engineering graduates along the desired lines.

A student desiring to work in petroleum engineering research would be much better equipped if he came without a single one of the so-called "professional subjects" in petroleum engineering but well grounded in the basic sciences, mathematics, hydraulics, thermodynamics, etc., of which he ordinarily has but a smattering.

Thorough Training in Fundamentals for Research Specialists

C. R. Fettke,* Pittsburgh, Pa.—The men who are to become research specialists for the petroleum industry should have a more thorough training in the fundamentals, mathematics, chemistry, physics, mechanics, and for many of the problems, geology. The man inclined toward research work should plan on at least an additional year to cover the more advanced phases of these fundamental subjects.

The actual conduct of petroleum research and particularly the training of men for such work is a field for a number of our universities to develop. Not all of the schools having courses in petroleum engineering or who are establishing such courses, are in a position to undertake such work, nor is it necessary or advisable that they do so. A few of our larger universities favorably located near the important producing centers ought to enter this field. If they have not the necessary personnel and facilities, they should acquire them.

I do not hesitate to recommend universities that already have such facilities. Also, just as the U. S. Geological Survey has been an excellent postgraduate training school for many of our prominent geologists, the U. S. Bureau of Mines is functioning in a similar capacity for many of our petroleum engineers who are inclined toward research work. The oil companies have utilized this source in making up their research staffs in the past and will undoubtedly continue to do so, provided these bureaus continue to attract young men thoroughly trained in the fundamentals.

The training of the research engineer must be such that he will know when to call on the physicist, the chemist, or other scientist who has specialized in a comparatively narrow field to cooperate with him on his problems.

The openings for research workers will always be very small as compared to the number of technically trained men that the industry is capable of absorbing for the routine work of operating. Those engaged in teaching in the engineering colleges should first make sure that a young man shows aptitude for research work before advising him to take up that work.

K. C. Heald.—To train men thoroughly so that they can meet our petroleum engineering problems, you must have schools that are adequately endowed and equipped. There should be a centralization of petroleum engineering courses. Very few schools should have such departments and then these departments would be so important that they could demand adequate support, equipment and faculty.

Two Types of Research

R. R. Brandenthaler,† Bartlesville, Okla.—There are two types of research, one of a purely fundamental character which often does not have an immediate practical application, and the other of a practical nature. In the Bureau of Mines we carry on both types with perhaps a preponderance of the latter. In the work which comes under my direction I find that the men who are most familiar with field practices and who have had field experience and are incidentally most aggressive in handling a field problem, usually develop into the best type of research men for our work.

In the work we are starting on natural flow and gas-lift experiments much progress could not be made unless at least the engineer in charge of the project has had a field background. More men available for the work with a good field background will expedite the completion of the problem. However, there are certain phases of the work for which a different type of man is required. I should like very much, for instance, to have a competent physicist available for special problems. Thus there is a

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† Petroleum Engineer, U. S. Bureau of Mines.

limited field for men having special training. These specialists need not, however, have any more knowledge of the production of oil than of some other line of endeavor.

We should not at the present time tackle research problems of too abstract a nature. The engineer must make a place for himself in the industry and the most direct method by which this may be accomplished is to keep in mind at all times the practical application of whatever research problem he might be engaged in.

I question whether we will ever be able to solve many of our problems in much the same way as the mining engineer. Too many empirical factors enter into our work to make petroleum engineering as exact a science as is mining engineering. Insofar as the type of work I am engaged in with the Bureau of Mines is concerned, our requirements call for men who have had a certain amount of field experience.

With reference to companies, I question whether petroleum engineering has advanced to the stage where a company is justified in having a strictly scientific research department. It is my opinion that any failures in the continuance of such departments are due primarily to the fact that the type of investigation carried on was too far removed from direct field application. Organizations other than industrial should carry on the fundamental research type of investigation. Such field is limited and I question whether too many men should be encouraged and specially trained in research work at this time by the universities.

Where Does Geophysics Belong in the Petroleum Engineering Curriculum?*

Introduction by L. C. Uren, Chairman

Petroleum engineering seems to have reached the stage of development where we must take cognizance of geophysics and give it some sort of a place in our curricula. We do not fully appreciate where it belongs in our program, whether it is identified with the work of the geologist or physicist, or whether it might be taught by the engineering departments, making principal application of it. We do not agree as to just where it belongs in the curriculum, whether it should be placed in the undergraduate or graduate curriculum, or perhaps in both.

DISCUSSION

D. H. McLaughlin,* Cambridge, Mass.—It is likely that there will be considerable variety in the way different schools handle the problem, depending on their particular facilities. In one case there may be a strong man in the subject in the engineering department; in another case a geologist may take the lead; in another, a physicist. As I see our problem at Harvard, the situation can be met most effectively by the addition to the geological department of a professorship of geophysics, with an assistant professorship and such assistants as necessary, with endowment for equipment, laboratories and maintenance. The work then would probably center around the existing seismological station.

As an introduction to the geophysical aspects of geology, perhaps one or two undergraduate courses might be given, designed to make geologists or engineering students acquainted with the field in a general way, but I think the major part of the work should be on a graduate basis.

Applied geophysics, *i. e.*, the geophysical prospecting, is a narrower field, and would appeal primarily only to students who were definitely specializing in petroleum

* Professor of Mining Engineering, Harvard University.

or mining geology. In our regular courses in petroleum geology and in mining geology at present enough time is devoted to the subject in undergraduate years to make the students familiar with the methods and the opportunities that exist. With courses in broader phases of the subject available in the geological department, and instruction in applied geophysics in the engineering school, I think we would be on a satisfactory basis to meet the needs of students preparing for general professional geological work, and also to offer opportunities for more intensive work in graduate years to men who desire to become specialists.

It is of particular importance in training geologists to see to it that they get enough physics and mathematics in their undergraduate years. I do not mean merely in connection with geophysical prospecting, but for good work in geology in general.

Place for Geophysics is in Department of Geology

H. C. George.—At Oklahoma this semester on account of the interest in geophysics for undergraduates, a course was established in the Department of Physics, I think at the request of the Department of Geology.

I think that the place for geophysics is in the Department of Geology under the supervision of some man who is specializing in that line. I think most of the geologists in the larger oil companies feel that a large part of the work, or a large dependence, at least, is going to be placed upon geophysics in the work of the average geologist in the future.

I think that the future of geology is rather in the engineering school than in the school of arts and sciences. At Oklahoma, whereas four or five years ago most of the geologists were majoring in geology in the school of arts and science, the tendency now is to major in engineering geology, and thus get all the necessary mathematics, physics and mechanics that a man should have in field work.

D. H. McLaughlin.—I would not be surprised to find that in 10 years instruction in the more standardized methods of applied geophysics will become an accepted part of routine geological education, comparable to the work with the petrographic microscope today.

Geophysics a Graduate Course

E. L. Estabrook.—Certainly the whole geological profession will gain by an increased amount of study of physics as a basic subject but I think that anything so advanced as geophysical work needs to be taught in a graduate rather than an undergraduate course. It is too much to expect an undergraduate to complete in four years his necessary basic studies and at the same time obtain sufficient knowledge of geophysics to enable him to go out into the field and do independent work.

D. H. McLaughlin.—I quite agree that the graduate school is the place for training specialists in geophysical prospecting, though there will always be a need for ready men fitted with the smaller amount of training that can be acquired in undergraduate years.

L. C. Uren.—Have you any ideas as to the period over which the graduate training might profitably extend in this field? Is it something in the nature of Ph. D. training? Is that desirable?

D. H. McLaughlin.—I should think so, ideally. A specialist in geophysics should not be on a lower plane than a specialist in applied geology and I think the Ph. D. training has established itself as proper for such men.

H. C. GEORGE.—The ability to interpret results, irrespective of the length of training in geophysics, depends largely on a man's experience as a geologist. A man not a good geologist by experience would be incapable of interpreting results by physics alone.

C. W. BROWN,* Providence, R. I.—May not this work be divided into two—the geologist to interpret the conclusions of the geophysicist whose training is necessarily different from that of the geologist?

PRESENT EMPHASIS ON INSTRUMENTAL TECHNIQUE

D. H. McLAUGHLIN.—Is it not true that at this particular time major emphasis is on development of instrumental technique and after a bit the emphasis is going to shift? We will accept instruments more or less standardized as we accept the petrographic microscope today and the main job will be interpretation. The geological phase of the work is likely to become more and more important as experience in instrumental technique becomes more common.

E. L. ESTABROOK.—From the standpoint of economics we would like to have the personnel as low as possible and not have both an expensive geologist and an expensive geophysicist in the same party.

C. W. BROWN.—Would a geophysical map prepared first for the consulting geologist solve that difficulty?

E. L. ESTABROOK.—My experience would indicate that much of the value of the work would be lost if the investigations of the geologist and the geophysicist were carried on separately.

D. H. McLAUGHLIN.—The geologist possibly needs to become more quantitive in his measurements, but the physicists in geophysical prospecting generally might be warned to avoid meaningless accuracy. I think there is a great place for the man who is good enough to combine both fields. It is difficult but I do not think it is impossible.

C. H. BEHRE, JR.,† Cincinnati, O.—I think this hinges on the way we train our undergraduates. If we give engineering training, we start them much farther in geology than when in the pursuit of a bachelor's degree in the liberal arts course they have to take social sciences, history, etc.; they thus usually enter their graduate work with much more geological background. The usual liberal arts bachelor, too, if he took in his undergraduate career the studies he now can take only as a graduate student, could do something with geophysics in his graduate years. I am speaking from personal experience because I have run into this in balancing liberal arts against engineering.

D. H. McLAUGHLIN.—I am afraid we will always have difficulty with our graduate students on account of the unevenness of their preparation. So many are undecided on their careers until they finish the liberal arts course.

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† Assistant Professor of Geology, University of Cincinnati.

Case Method of Teaching Geology to Engineers*

By C. W. Brown,† Providence, R. I.

(New York Meeting, February, 1929)

SUMMARY

In the author's experience and contact with engineering students the old form of recitations had grown into the lecture system in which the student was a passive receiver of digested material. Later, the tutorial system was developed because it was felt that the lecture system was breaking down. The student was too passive and was simply trying to absorb what was given him. The seminary method was then introduced and for the particular field the author believes that there is no better method, but that for 20 years he has been trying to change the attitude of the student in certain courses from a passive, almost noncommittal, to an active participation, to change him from a receiver to a doer.

The student cannot look over the whole field. That must be presented by the instructor in charge. A topic such as structure or glaciation is taken up and from that standpoint are argued all the geologic problems that might confront the engineer. Problems relating to dams and foundations, and structures, tunnels and excavations, are particularly adaptable to the method. Usually, however, the problem comes to the engineer in more complicated form.

By virtue of the character of the material the same topic cannot be assigned to the entire class. Different phases of the topic must be assigned. The greatest difficulty in after life comes in that the student cannot analyze the problem and has not the ability to see that there is a problem. He has had little or no training in the gathering of material and very little training in the arrangement of a report. Consequently, selecting different problems, putting them before small groups, and then starting the student on the way to make the knowledge of his particular topic an integral part of his own mentality, is something that will fix that part of the work firmly in his mind.

Professor Brown has insisted on an introductory step in a great many classes, in that without the student knowning very much more than the general outline of the topic or problem, he is made in inductive fashion to take up the entire problem, look it over, and prepare an outline as far as he can; in other words, to expose the problem to his own mind. This preliminary outline is discussed with the student and if the arrangement or logic, with regard to the end in view, are faulty, he is shown where

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* Summarized from stenographer's report.

† Associate Professor of Geology, Head of Geology Department, Brown University.

the fault lies. Then he is set to work on his material, his reading, his method of extracting material.

The problems presented group together under simple topics and are easily applied to the structure or occurrence of oil, for instance, in the northern part of the California field as opposed to the southern part, or the Wyoming field, and would, when the reports are read or summarized by the student in class, result in a rather comprehensive view of the entire class upon the general topic. This method, too, gives the student a grounding in English that he cannot get elsewhere because the discussion of his treatment of the problem is based on technical knowledge.

DISCUSSION

In discussion it was developed that the case method is applied to field problems as well as to problems around the conference table. The method can hardly be employed with elementary classes. Professor Brown is conducting a class in engineering geology in which he takes the problem as outlined above, and is meeting each man for a half hour or an hour in conference each week, preferably two half hours at different times, accommodating two or three men at the hour, going over the work with them and showing them their mistakes. College students are not naturally lazy, but vigorous, and they hate to sit in lectures and be hypnotized for 15 hours a week by a voice to which they have no reply. They respond to an opportunity to do a little work themselves.

Prof. C. A. Bonine* reported that he is conducting a sophomore class in elementary geology. He lectures twice a week and early in the fall gives them, generally teaming two students together, individual areas of field work, requiring a report, which is criticized in conference. He finds that the student has more interest in listening to the lectures and that the problem method works with a beginner as well as with juniors and sophomores. The critical part of the problem is the student's ability to analyze. The summary of his report is especially emphasized.

Professor Brown does not favor four students working on one problem or two groups of two students each working on the same problem. Four on a problem, unless it is a very wide problem, and he prefers the narrower ones, is too large a number; the poorer members of the group learn quite a bit but the problem is really handled by the superior mind of the group. Professor Brown prefers to rate his men on individual problems rather than to put them in groups.

Professor R. H. Johnson† believed the case very strong for some project work of this sort somewhere in the curriculum. His own experience had led him to put it in the senior year, so that each man works on his own problem—usually two problems, one in the nature of field work and the other laboratory work—and approaches as nearly as possible a publishable research as the time permits. His thought is to encourage the attitude and habit of research and also to make a step toward the problems some of the men actually do get later on.

Professor D. F. McFarland‡ said that in the present year there were 14 seniors in metallurgical engineering at Pennsylvania State College. In the first semester there is a course which is a weekly conference, where the men pick their topic for investigation. This is wide enough to touch on one of the big fields of metallurgy

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† Professor, Oil and Gas Production, University of Pittsburgh.

‡ Professor of Metallurgy, Pennsylvania State College.

and narrow enough to permit real experimental work on some special portion of the topic. The students are early asked to state how they are going about the solution of their problem. In another report they present a statement of the present status in the field; in a third report, late in the semester, they summarize all that they have done. Each member of the class is given an oral examination on the work of the others. All thesis problems are, wherever possible, related to actual plant or at least live commercial questions. The same plan is followed in the second semester, one week of conference and at least eight hours of laboratory work. Each man's work is reported finally as a thesis, with careful attention to the form of the report.

Professor L. C. Uren * endorsed this method on the basis of his experience at the University of California, where it is handled along lines similar to those described by Professor McFarland, and is confined entirely to the senior and graduate years. He agreed that it might profitably be extended down into the lower divisions. Weekly contact with every student was maintained by half-hour conferences and progress carefully noted. In the seminar work a rigid schedule was adhered to.

Professor Brown stated that in the instance of the engineering group, four or five topics were assigned during the first semester and two or three-men groups made up around each topic. Instead of being given a half year in which to procrastinate, the students were given only three weeks.

Professor D. H. McLaughlin † pointed out that the method discussed by Professor Brown is similar in certain respects to the case system at the Harvard Law School and the Harvard School of Business Administration. He believed that it has great possibilities for use in engineering and geological educational work, but the difficulty and expense necessary to secure effective and properly complete cases should not be underrated.

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* Professor of Petroleum Engineering, University of California.

† Professor of Mining Engineering, Harvard University.

Chapter VII. Petroleum Refining

Developments in Refining of Petroleum and Its Constituents for the Year 1928

By H. W. Camp,* Tulsa, Okla.

(New York Meeting, February, 1929)

The past year has had no revolutionary change in the process of petroleum refining, although there have been improvements and developments in practically every phase of operation, due largely, perhaps, to economic pressure.

A few years ago, a Mid-Continent skimming plant using 35° gravity crude obtained 28 per cent. gasoline and naphtha; 9 per cent. kerosene, and the remaining yield gave gas oil and fuel oil. Figuring manufacturing cost, but not including sales, transportation, overhead and depreciation, the realization was $1.45 per bbl. of crude. Today, a thoroughly modern and up-to-date skimming plant, having all latest equipment, shows a realization of $1.74 per bbl. on the same basis. Thus it is evident that progressive developments have taken place in the last 2 or 3 years when potential earnings have been increased about 20 per cent.

The average refiner is compelled to exert his utmost ingenuity in order to operate with a profitable margin. He has two factors to consider—recovery of maximum yields of profitable oils and the reduction of operating expenses.

For the past 8 years, the margin between price of gasoline and cost of crude has grown narrower, constantly. Both these prices are determined by external conditions and not by the refiner himself, but the refiner might have been able to increase that margin had he more carefully controlled his output, limiting his production of light oils to current consumption. Be that as it may, this same economic pressure has given impetus to progress in improvements of primary distillation equipment, including stills, towers and heat-saving devices. A pipe still and bubble cap fractionating equipment can now replace a battery of shell stills, giving better yields, better control, elimination of rerunning and lowering of operating costs. The most recent pipe stills are being equipped either with radiant-heat furnaces or air-preheating systems and improved heat exchange equipment. These can be operated on a fuel consumption as low as 1 per cent. of the charge as compared to a fuel consumption of

* Refining Division, Empire Oil & Refining Co.

3.5 per cent. of charge on shell-still batteries. Fractionation is now so controlled that almost any separation desired can be effected in one operation. Streams can be separated so that only a portion of the products will require treating or can be divided so as to retain antiknock properties and at the same time eliminate gum-forming substances.

It is sometimes uneconomical to write off a big investment of shell stills. Instead of abandoning these, it has been found profitable to equip them with air preheaters, improved furnaces, bubble cap towers and heat exchangers so that their efficiency may be comparable to pipe-still installations. A recent development in shell-still design is the addition of interior tubes with suitable headers, which has improved the efficiency and presents a further possibility of utilizing old shell-still batteries profitably.

There have been no recent marked changes in methods of treating in general but many improvements have been made and several new processes have been developed for special classes of oil. There is a tendency toward the installation of continuous treating systems in preference to batch agitators. The adoption of recirculation in agitators has made a big improvement in batch treating. Regeneration of caustic is employed and the material is used repeatedly until causticity is as low as 2 per cent. Acid-recovery systems are used which recover as much as 80 per cent. of the acid, and even the litharge for sweetening gasoline is recovered many times over.

Operating expenses have been cut materially and refinery efficiency increased because of several factors, such as: (1) better boiler-house practice and more efficient boilers; (2) production of dry and superheated steam; (3) utilization of exhaust steam and feed-water treatment; (4) installation of boilers for higher steam pressure, in connection with bleeder-type turbines, which enables the refiner to generate electricity for refinery use at practically no added cost, as well as to utilize the same steam for regular processing; (5) water-cooled walls in boiler settings, which increase materially the rating of the boiler.

Acid sludge is now used for fuel while heretofore it was not only a waste product but also a nuisance.

Losses have been decreased through the installation of vapor-recovery systems, vapor-tight and floating roofs, acid-sludge and B. S. recovery systems, and improved methods of loading and unloading volatile oils. Vapor-recovery systems gather gases from stills, tanks, agitators and loading racks; these gases are passed through an absorption process and about 85 per cent. of the gasoline is recovered. The residue is burned for fuel.

The largest single factor for the advancement of refinery practice is the pressure still. Add sufficient cracking capacity to a skimming plant, in order to convert the heavier fractions into gasoline, and the

yield increases from 32 to 66 per cent. The realization from a barrel of crude, considering higher manufacturing expense, increases from $1.74 to $2.44 per bbl. and the gallonage of gasoline from a barrel of crude is doubled. Without the advent of the pressure still, it is doubtful whether the refiner could have kept pace with the rapid and tremendous increase in gasoline consumption. Had the refiner attempted to increase his skimming facilities to meet the gasoline consumption, obviously the fuel-oil market would have been glutted, and hence demoralized. Three factors are responsible for the rapid and efficient development of the pressure still: (1) the necessity for securing ultimate yields for economic existence; (2) the necessity for increased gasoline recovery in order to stay abreast of the rapidly mounting consumption and (3) curtailment of the fuel-oil market with consequent reduction of selling price. Wider natural-gas distribution, particularly in the Middle West, together with determined competition from the coal industry, has materially affected the fuel-oil situation and added a very strong incentive toward the necessity of obtaining the maximum yield from a barrel of crude by cracking.

It is doubtful whether the crude-oil producers took into account a few years ago the fact that the refiners had opened a way to doubling their gasoline yield by the installation of modern equipment. Overlooking the fact that one barrel of crude produced the same amount of gasoline formerly produced by two barrels, the producers maintained a steady increase in production, so that when coupled with increased ultimate recovery, the production of gasoline far exceeded consumption and as a result, the oil industry passed through an era where there were no profits.

There have been no big innovations or radical changes in liquid-phase cracking equipment during the past year or so, but there have been many improvements and the present trend is toward units of larger capacity, higher fuel efficiency, finishing gasoline direct from units and controlled operation, so as to produce gasoline with better antiknock properties. Higher operating pressures, reduction of coke and fixed gases, retardation of corrosion and other problems are being worked out, so that we may expect to see improvements. Methods are being developed to recover valuable by-products, including alcohols, esters and various types of synthetic products.

Much progress has been made during the past year in the development of the vapor-phase pressure still. Several workable processes have been developed and a number of commercial installations have been made. Gasolines having high antiknock properties are produced by this method. The vapor-phase pressure stills produce a larger quantity of fixed gas than former processes. This gas has a large unsaturated hydrocarbon content, which may be recovered and probably converted into valuable products through synthetic chemistry.

The recent production of crudes having high sulfur content has presented a new problem to the refiner by corrosion of his equipment; indeed, distilling equipment has been eaten up in a few months when distilling this crude. The refiner is attempting to combat this condition to the best of his ability by pretreatment of crude with alkalis, by injection of ammonia and caustic into vapor lines, condensers, exchangers, towers and stills, or by similar methods. Liquid caustic is added in rundown lines to eliminate corrosion in lines and tanks. Various types of leadclad roofs and coatings of protective paint are used in tanks. There is the possibility of the use of aluminum tanks for resisting corrosion, as they are not affected by the various sulfur compounds.

The pressure still presents the most vital problem of corrosion in the refinery, since there is not only the high cost of replacement to be considered but also the element of operating danger. Various methods of reducing corrosion in pressure stills have been evolved, as lime injected into charging stocks, the adaptation of various alloys in valves, lines, tubes and chambers, chief among these corrosion inhibitors being chromium and nickel. One of the outstanding developments of this year has been the development of non-metallic coatings for interiors of cracking chambers as well as liners.

Production of lubricating oils is another profitable phase of operation and one which balances out the refinery. The investment is high and the operation complex; however, the return is good and the price and consumption are fairly stable.

Several new features have come into practice in regard to the processing of lubricating oils in recent times. Vacuum distillation in all its aspects is probably foremost among these. For some time vacuum distillation has been successfully applied to batch shell stills in the production of asphalt-base crude oils. The latest development has been to adapt the pipe still to vacuum-still practice, using suitable fractionating equipment designed to make as many cuts as desired. Overheating of oils causing breaking down is avoided in this type of installation and maximum yields of lubricating oils are secured. A new development in vacuum-still practice is the use of an indirect heating medium such as mercury vapor or diphenyl.

The atmospheric pipe still and bubble cap tower have been applied to the reduction of pressed distillate and the yields greatly increased. For some time the sulfur dioxide method of treating has been applied to light oils, and recently this treating has been applied to lubricating oils manufactured from certain crudes, with favorable results. Lately commercial production of wax-free oils from paraffin-base oils having low cold test has been developed.

The refiner cannot claim all the credit for the development of improved equipment, as the manufacturers themselves have contributed largely

to this constructive progress. Cooperation and distribution of information between the refiners and manufacturers of equipment have led to a better understanding of the problems involved and permitted a much more widespread utilization of up-to-date processing. Space will not permit the naming of dozens of improvements which are small and highly technical but which have a vital part in plant operation. The development of the art of welding has played a very prominent part in the advancement of refinery technique, since many pieces of equipment are in use which would be almost impossible to construct and maintain were old pipe-fitting methods employed.

One of the most interesting, if less specific, developments of recent times is the stimulation of research, especially cooperative research. Perhaps the art of refining was much retarded by the rather futile method of independent research, as much progress and effort were duplicated. The old way was to consider every development a trade secret while today the refining industry is considering programs of cooperative research to expedite the industry as a whole.

Chapter VIII. Gas Transportation

Design of High-pressure Gas Pipe Lines

By Ralph E. Davis* and Lyon F. Terry,† New York, N. Y.

(New York Meeting, February, 1929)

The rapid expansion of the natural gas industry in this country during the past three or four years has necessitated the construction of a number of long and comparatively large diameter high-pressure pipe lines. This period of expansion and construction is still at high tide, and the current year will doubtless surpass all prior years in mileage and capacity of gas line installation.

The fundamental economics of the business of long-distance transportation of natural gas may be briefly and simply stated, although most careful consideration must be given the actual determination and integration of the several more important factors which determine the ultimate success or failure of such a project.

Reduced to its simplest form, a sound natural gas transportation project requires:

1. A competent source of gas, where the combination of quantity of gas available, cost of production, and longevity meet the given requirements.

2. A market, reasonably certain to endure in the face of any probable competition, of satisfactory size and price, and having a sufficiently favorable load factor.

3. A cost of installation of pipe line system and an operating cost such as will, with honest and reasonably efficient management, afford a net operating return sufficient to attract the necessary capital required.

In all new projects of this kind it is necessary that these three essentials to ultimate success be assured. Hence the necessity of competent surveys of gas supply, and of market, both industrial and domestic. The prudent engineer will allow for "factors of safety" in reaching his conclusions just as he would in the design of a bridge.

This paper deals primarily with but one of the major considerations enumerated above, *i. e.*, the economic design of the pipe line system. The "pipe line system" will be considered to include (1) the pipe line, and (2) a series of compressor plants along the pipe line for maintaining

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† Engineer, associated with senior author.

the necessary pressure. Inasmuch as there is necessarily an intimate relation between the size (diameter) of line required and the number and capacity of compressor plants appurtenant thereto, as also a direct relation between both of these and operating cost, it is necessary to discuss all three to some extent. However, the subject of operating costs is introduced only to such extent as is necessary in the exposition of the principles controlling the economic design of the pipe line and compressor plants.

Pipe Line Materials and Costs

The pipe line is constructed of steel pipe in lengths of 20 to 30 ft. Steel is required instead of cast iron since design calls for the withstanding of high pressure up to 300 to 600 lb. per sq. in. The steel used varies in ultimate strength from 45,000 to 65,000 lb. per sq. in., with the trend in manufacture toward the higher figure. Lap-weld pipe has generally been used, but recently there has been successfully developed pipe with electrically welded seams; and for diameters up to 14 in. certain manufacturers are now featuring seamless pipe. The joints of pipe are laid under ground with usually from 2 to 3 ft. of cover and joined with sleeve and flange couplings made tight with rubber gaskets, or by welding. Gate valves are inserted in the pipe line at distances of 6 to 10 miles so that in case of changes being required or leaks or blow-outs occurring, any section of pipe line may be isolated and drained if necessary.

The pipe itself costs in large quantities at present prices about $70 to $80 per ton f.o.b. mills and from $10 to $20 per ton for freight, depending upon locality. The coupling or welding cost varies from 15 to 20 per cent. of the cost of the pipe. The construction labor depends upon the weight and diameter of pipe and the nature of the country, varying from $3000 to $6000 per mile for 20-in. pipe. Right of way and survey costs run $500 to $1000 per mile depending upon local conditions. Generally a telephone system is built along the pipe line at a cost of about $400 per mile. Of the above items of investment, the principal one is the pipe itself so that the total cost will vary approximately with the tonnage.

Compressor Plants—Type and Cost

The flow of gas through a pipe line is caused by a difference in pressures, and to create this pressure differential one or more compressor plants are built along the line. In long lines these compressor plants consist of a series of booster stations and the flow of gas between booster stations depends upon the pressure at the discharge of one station and the suction pressure at the following station. The compressors at a station are generally single stage, gas-compressing cylinders directly

driven by four-cycle gas engines. Auxiliary machinery such as water-circulating pumps, electric light and power system, cooling coils, interchangers, water towers, tanks, water supply, etc., as also proper plant buildings and residences for operators are required.

The cost of compressor plants depends upon the quantity of gas to be compressed, the compression ratio, and secondarily with the type and weight of compressors, quality of buildings and the extent and quality of appurtenances. The cost will run from \$100 to \$140 per horsepower of main units plus a fixed investment of from \$40,000 to \$100,000 or more for general construction, at any large station regardless of size. On long and large gas lines developed to full capacity the compressor plants cost from 20 to 25 per cent. of the total system.

Fitting a Pipe Line to Meet Its Particular Requirement

Every natural gas transmission line is designed to meet the particular requirements that it is built to serve. The length of line is known. The quantity of gas that can be sold profitably is estimated, and the fluctuations in daily and hourly delivery requirement are determined as accurately as possible. Gas used for domestic purposes affords a higher price but gives a very low load factor. Gas used industrially must be sold at a lower price but due to the more even demand improves the average load factor materially. The operating cost per M cu. ft. and the investment cost per M cu. ft. will be inversely proportional to the total quantity handled and also inversely to the load factor.

After having assembled the necessary preliminary data, the first step in pipe line design is to assume a size of pipe that gives approximately the desired capacity. Inasmuch as the ultimate capacity required is generally greater than that needed in the first year or two of operation, it is economical to select a diameter of pipe somewhat larger than is at first essential, and to construct at the outset only a part of the ultimate compressor capacity. The most economical combination of line diameter and quantity and spacing of compressor units is found after a consideration of the interrelation of several factors, as is developed in the following discussion.

Design

The pipe line system consists of two parts, the pipe line and the compressor plants. Hence, we will first examine the significance of those factors primarily affecting the pipe line and then treat the factors primarily affecting the compressor system, with the intent of presenting a method of selecting the most economical design suitable for any given pipe line requirement.

The flow of gas through high-pressure gas lines may be most accurately represented by the generally accepted formula of Thomas R. Weymouth,[1] stated as follows:

$$Q = 871\ D^{8/3} \sqrt{(P_1^2 - P_2^2)/L} \tag{1}$$

Where, Q = cu. ft. per day at 14.65 lb. per sq. in. absolute pressure at 60° F., sp. gr., 0.60

D = inside diameter of pipe in inches.

P_1 = absolute pressure lb. per sq. in. at intake into pipe line (or discharge of compressors).

P_2 = absolute pressure lb. per sq. in. at discharge from pipe line (or suction into compressors).

L = length in miles (distance between stations).

It will be necessary to give attention to the thickness and weight of pipe, to the cost of pipe line and cost of compressor plants. For convenience the following symbols will be used:

T = thickness of pipe.

W = weight of pipe, dependent upon D, T and L.

C_p = cost of pipe line.

C_c = cost of compressor plants.

C_t = total cost of complete system.

In the flow formula (1), the factors primarily affecting the size of the pipe D are Q and P_1, while L represents the distance between compressor plants. P_1 is proportional to the pressure differential factor $\sqrt{P_1^2 - P_2^2}$ providing the compression ratio, P_1/P_2 remains constant, as we shall here assume. It follows that if the diameter of pipe is assumed to be increased the maximum pressure may be proportionally decreased without change in the combined result, so that the selection of diameter is dependent upon maximum working pressure designed for, and vice versa. Let us consider, then, the significance of the diameter and the pressure at first separately, and then taken together, as follows:

Effect of the Diameter

First, assume all variables on the right-hand side of the flow equation (1), excepting diameter, to remain constant while we observe the effect upon capacity of changes in diameter:

If D is increased 10 per cent.

Then, Q is increased 29 per cent. (varies as $D^{8/3}$)

C_p is increased 21 per cent. (varies as D^2)

C_c is increased 29 per cent. (varies as Q)

C_t is increased 22.6 per cent. (if C_c = 20 per cent of C_t)

$C_t Q$ is decreased 5 per cent.

[1] T. R. Weymouth: Measurement of Natural Gas. *Trans.* A. S. M. E. (1912) **34**, 1091.

The cost of the pipe varies directly as the weight of the pipe, which varies directly as the diameter times the thickness. With increasing diameters the thickness of the pipe must be increased proportionately to withstand the same pressure. Thus, since maximum pressure is here assumed to be constant, the cost of the pipe varies as the square

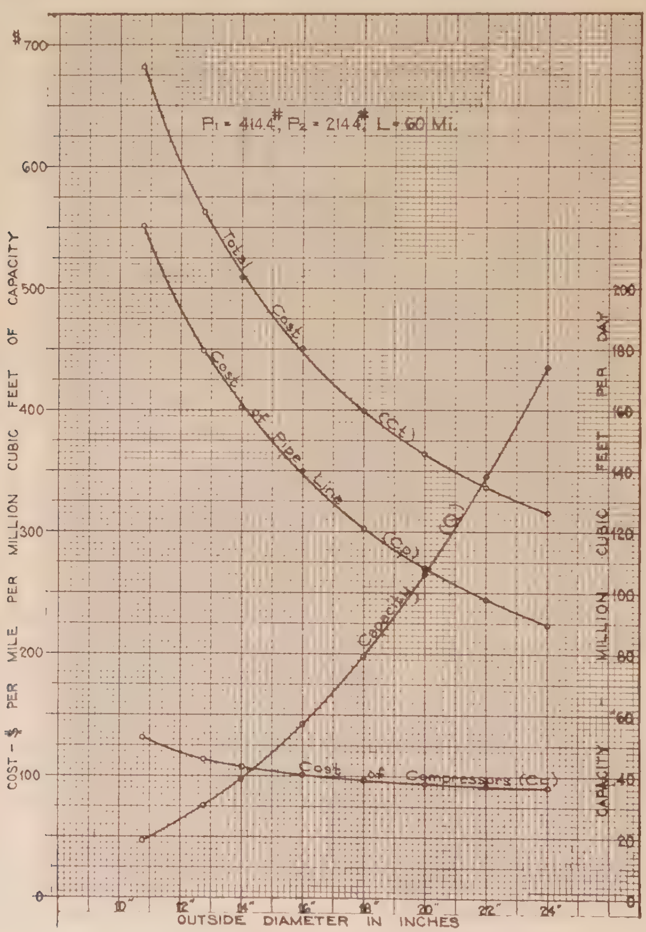

FIG. 1.—VARIATION OF CAPACITY WITH DIAMETER.

of the diameter. The capacity of the pipe line, however, varies as the 2.667 power of the diameter. Hence, increasing the diameter will increase the capacity very rapidly and in excess of the increase in the cost. That is, other factors being assumed constant, the larger the diameter the larger the capacity and the lower the investment cost per million cubic feet of capacity. This relation is represented graphically in Fig. 1.

Effect of Pressure

The differential in pressure causing the flow of gas along the pipe line is caused and controlled by the compressor plant system. The principal operating characteristic of the compressor plants is the compression ratio maintained, represented by $R = P_1/P_2$. Assuming this ratio to remain constant the factor $\sqrt{P_1^2 - P_2^2}$ varies directly as P_1 and we may substitute aP_1 in the flow formula in place of the member $\sqrt{P_1^2 - P_2^2}$. The relation between P_1 and Q (assuming the other factors

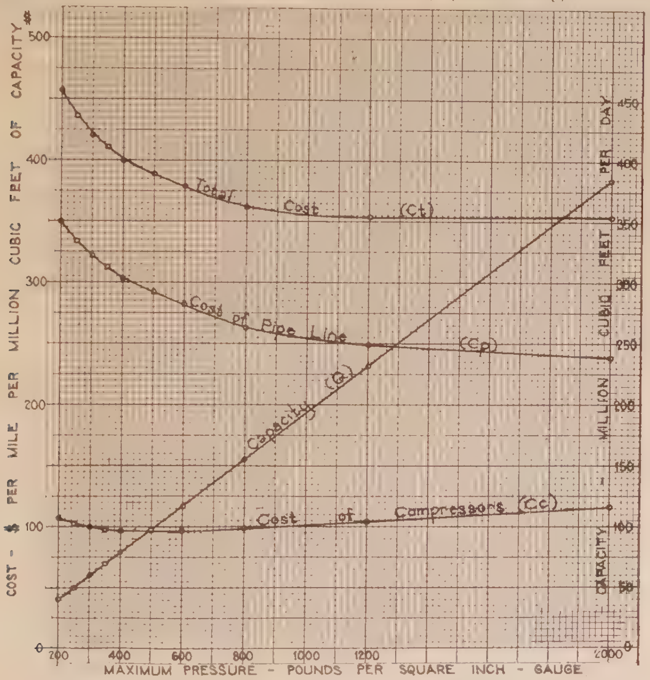

Fig. 2.—Variation of capacity with pressure.

D = 18 in., R = 1.93, L = 60 miles

D, R and L to remain constant) and the costs of the investment at different assumed pressures are presented graphically in Fig. 2. Investment costs per mile per million cubic feet per day of capacity have been calculated for this and the other accompanying charts by the following formulas:

$$C_c = (\$120 \text{ per hp.} \times \text{hp. per } M^2 \times 115 \text{ per cent.} + \$50{,}000 \div Q) \div L \qquad (2)$$

$$C_p = (\$120 \text{ per ton} \times \text{tons per mile} + \$125 \times D \text{ in.} + \$1250) \div Q \qquad (3)$$

$$C_t = C_c + C_p, \text{ all in dollars per mile per } M^2 \text{ per day of capacity} \qquad (4)$$

The equation for C_c above includes 15 per cent. for spare compressor units and assumes a general construction cost of $50,000 at each plant regardless of size. The graphs representing compressor costs at different

pressures have been given higher unit values at pressures above 500 lb. than shown by the simple equation for C_c above, in order to take care of expensive special valves, fittings, coolers, etc., required for excessive pressures.

In the equation for C_p above, the cost of pipe, couplings, main valves and most of the construction labor is included in the $120 per ton. Certain charges vary directly with the diameter, such as paint and to some extent labor, ditching and backfilling. Also other fixed amounts, taken above at $1250 per mile, need be spent for survey, right-of-way, telephone lines, etc., regardless of weight, diameter or pressure. The curve C_t shows that the total investment cost per unit of capacity decreases with increases in pressure until exceedingly high pressures are reached and thereafter it is practically constant. However, at exceedingly high pressures the operation of the line would be dangerous and difficult, and hence more expensive, even though the investment cost per million remains practically constant.

Thickness of Pipe

The wall thickness of the pipe should be designed to fulfill both of the following two requirements:

1. To withstand bursting from internal pressure of the gas, the wall thickness in inches should be not less than:

$$T = \frac{\text{Outside diameter} \times \text{maximum pressure}}{2 \times \text{allowable working stress}} \quad \text{(Barlow's formula)} \quad (5)$$

2. Regardless of thickness to withstand gas pressure, the wall of the pipe must be not less than a safe, practical, minimum thickness, sufficient to withstand bending stress, rough handling in shipping and construction, to permit of welding and fire-bending in the field and to make proper allowance for the effect of corrosion after construction. What this minimum wall thickness should be depends upon the size of the pipe, quality of the steel, possibility and effect of corrosion with due consideration to pipe protection employed, construction difficulties and other things determined by conditions of the particular case. For large diameter pipe this minimum thickness should not be less than, say $\frac{1}{4}$ to $\frac{5}{16}$ inch.

The wall thickness of the pipe then must be not less than (1) or (2), above, whichever is greater. And if the thickness necessary to fulfill requirements of (2) above is greater than that necessary to withstand bursting under the assumed maximum pressure, then, of course, the assumed maximum pressure should be increased to that provided by the thickness necessary to satisfy the practical requirements of (2). To illustrate: 16-in. pipe of a steel whose allowable working stress may be taken at 10,000 lb. per sq. in. would require a thickness of 0.16 in. if designed for a maximum pressure of 200 lb. per sq. in. according to (1)

above. But, according to (2) above this thickness of 0.16 in. is entirely too thin for practical purposes, and the pipe line should be built of not less than, say, 1/4 in. wall thickness. By (1) above the 1/4 in. wall thickness would provide a maximum working pressure of 312 lb. per sq. in. which should be made use of.

Relation between Diameter, Pressure and Thickness

For any given diameter of pipe there is a corresponding working pressure; these two factors taken together will produce the same capacity

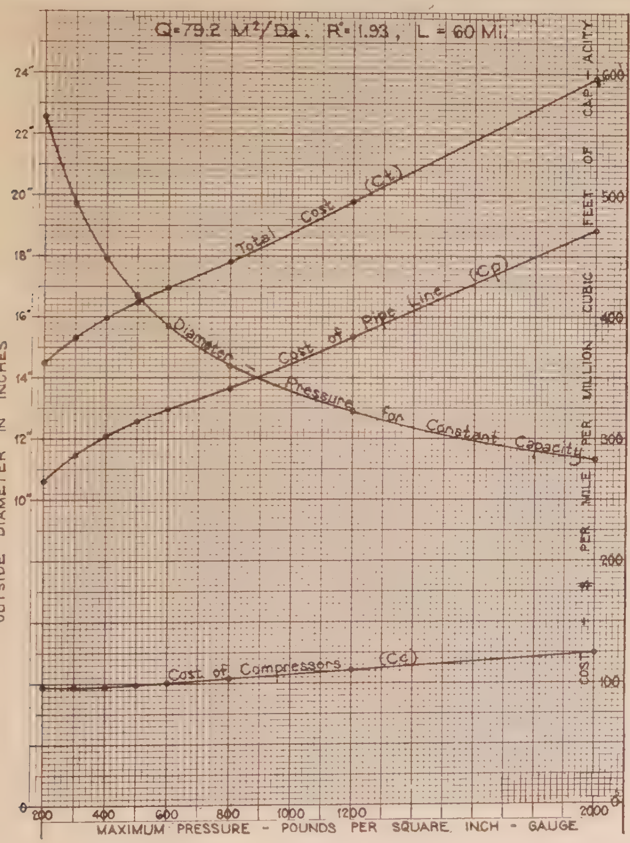

Fig. 3.—Variation of diameter with pressure.

of line. This is presented in Fig. 3 by a curve, any point on which represents the diameter and corresponding maximum pressure having a constant delivery capacity. It may be observed from this chart that should an 18-in. line with 400 lb. maximum pressure be necessary to deliver a required volume, and should we attempt to discover a more economical choice of pipe, it is more economical to increase the diameter

and reduce the pressure, rather than to reduce the diameter and increase the pressure, without changing the resulting capacity. This relation exists for the reason that increases in diameter increase the capacity more rapidly than they increase the cost; while changes in pressure have more nearly equal effect upon capacity and cost.

In the selection of size and weight of pipe, with corresponding allowable working pressure it is therefore economical to choose as large a diameter as possible, without exceeding either of the two following limits:

1. The wall thickness of the pipe must not be less than a safe, practical minimum, regardless of its bursting strength. The working pressure designed for should be not less than that provided by said minimum practical thickness; and it need not be more. The diameter, then, should be made just large enough so that at this designed pressure the capacity of line will fulfill delivery requirements.

2. The diameter should not exceed that which may be practically and economically manufactured by the pipe mills, at the present time 22 to 24 in. for lapweld pipe.

Any pipe of large diameter should not be operated at pressures in excess of practical, safe limits of from 400 to 600 lb. and the latter only in special cases, where the quantity to be transported requires a diameter approaching the practical maximum, or where available pressure of the gas wells in the field can be made use of without artificial compressing. It would not be economical to transmit natural gas long distances under excessive high pressures.

The above points of economy in design are illustrated and taken advantage of in the so-called "telescope line," made up of sections of diameter increasing in the direction of flow with decreasing pressures. For example, where a 16-in. line was required, its equivalent has been built of 14, 16 and 18 in. Such a design results in a larger average diameter of pipe, with a resulting smaller average maximum pressure to be designed for and has the effect of making the total weight of pipe required slightly less than for the equivalent straight pipe line of uniform diameter. The telescope design is especially economical where very high pressures and long distances between stations are planned; for instance, where high pressures in the gas field are taken advantage of at the field end of the pipe line.

Protection against Corrosion

The principles of design developed above may be safely followed providing the pipe is properly protected against corrosion by adequate paint or pipe coating. The economic value of good pipe coating has become more and more appreciated during the last few years in connection with the recent construction of extensive pipe lines; and much more

care is being taken to prevent corrosion in present pipe line practice than formerly.

The amount of money which is warranted to be spent upon pipe coating, as well as the kind of coating indicated depends upon the nature of the soil through which the line lies and the relative corrosive effects to be expected under the conditions. It is quite evident that if the life of a pipe line in the ground can be prolonged 50 per cent. by the applica-

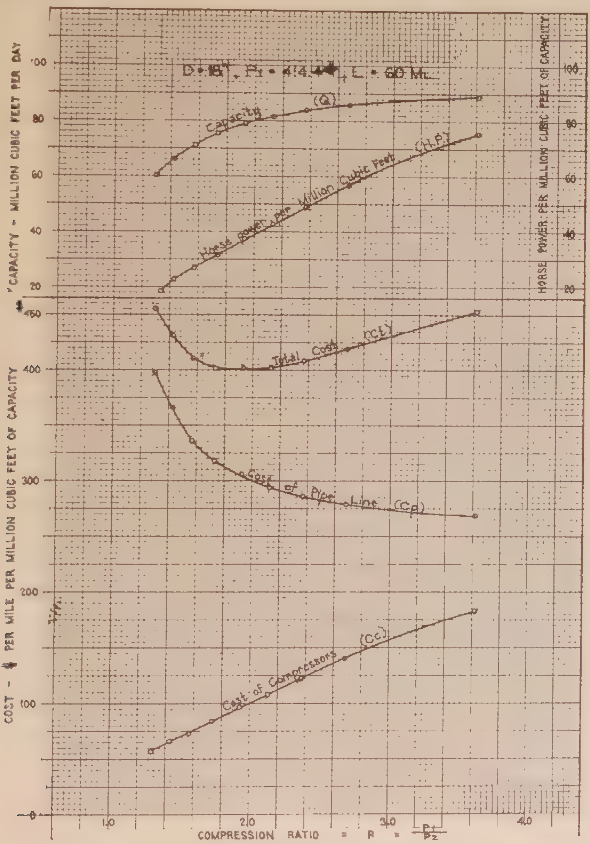

FIG. 4.—VARIATION OF CAPACITY WITH COMPRESSION RATIO.

tion of a good grade of pipe coating it is worth much more in the long run to the total investment than the 6 or 8 per cent. of same that it costs.

Compressor Plant System

In the flow formula (1), the relation between P_1 and P_2 and the distance between stations L are controlled by the installation of compressors and the spacing of compressor plants, which we shall now consider. All of the gas transported by the pipe line needs to be handled by each

compressor station. The horsepower HP required at each station varies directly with the quantity Q, and is also a function of the compression ratio R, maintained by the compressors:

$$HP = Q \times f(R) \tag{6}$$

Effect of Compression Ratio

The relation between the compression ratio, the capacity of the line and the investment costs are shown in Fig. 4. On this chart the diameter, the distance between stations and the maximum pressure are assumed to remain constant. For increases in the compression ratio the horsepower required per million cu. ft. increases as a straight line; while the capacity increases more rapidly than the horsepower, up to a certain point (which, for the particular characteristics here assumed constant, lies between $R = 1.8$ and $R = 2.0$). But after this point is reached the capacity increases more and more gradually and less in percentage than does the horsepower required. The cost per million of the compressor system is practically proportionate to the total horsepower required for all stations. The cost per million of the pipe line is inversely proportional to the quantity of gas handled. Thus for any given conditions there is a critical compression ratio to be designed for, at which the total cost of the system per unit of capacity will be a minimum.

In practice station sites should be located if possible on high ground accessible to highways, railroad, water supply, etc., and slight changes in compression ratio may be made to permit theoretical station spacing to fit geographical conditions.

Effect of Distance between Stations

Other things being equal, the capacity of the system varies inversely with the square root of the distance between stations (L). The cost of the compressor system varies inversely with the distance between stations. Thus,

If L is decreased 10 per cent.

Q is increased 5.4 per cent. $\left(\text{varies as } \dfrac{1}{\sqrt{L}}\right)$

C_c is increased 17 per cent. $\left(\text{varies as } \dfrac{Q}{L}\right)$

C_p is increased 0 per cent.

C_t is increased 3.4 per cent. (if C_c = 20 per cent. of C_t)

C_t/Q is decreased 2 per cent.

From the above it appears that:

1. The cost of the pipe line being fixed, the cost per million of capacity will become less and less as L decreases and increases the flow.

2. That opposing this relation it requires twice the number of plants (and twice the plant operating expenses) to cut the distance between stations in half.

3. That at some point there is a critical distance at which a minimum cost per million cu. ft. of capacity occurs. In Fig. 5 this point is seen to lie at about 40 to 45 miles under the conditions assumed. However, for different conditions the critical point changes. The conditions assumed in the chart are for an 18-in. pipe with 400 lb. maximum pressure, 200 lb. downstream pressure, transmitting 79 million cu. ft. per day. If the

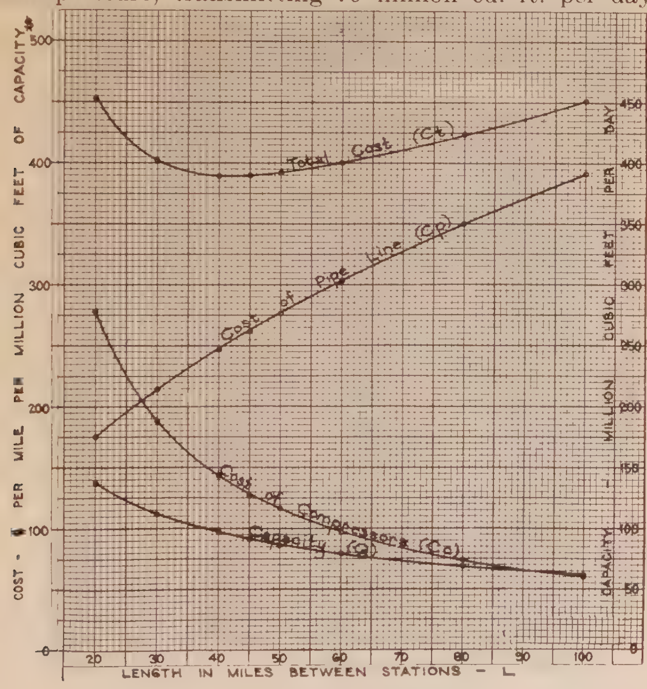

FIG. 5.—VARIATION OF CAPACITY WITH STATION SPACING.

$D = 18$ in., $P_1 = 414.4$ lb., $P_2 = 214.4$ lb.

quantity to be transmitted is reduced to 60 million ft. per day, then the critical distance of minimum investment becomes 80 to 100 miles between stations.

This relation between L and Q is nicely taken advantage of in practice by building stations far apart to start with; and when and as the business and market at destination increases sufficiently to warrant expansion, stations are built in between those originally constructed so that the distance between stations is reduced by 50 per cent.

The quantity of gas transported through a given line will be constant, provided the proper relation between compression ratio and distance

between stations be maintained. This is illustrated in Fig. 6. For a given size of pipe and a given required delivery there is a limiting distance beyond which it is impossible to force the required volume through the pipe line, no matter how great a compression ratio may be maintained. It will be observed on the chart that the compression ratio increases gradually with increases in L until this limiting distance is approached, and then the ratio curves rapidly upwards. We have plotted on this

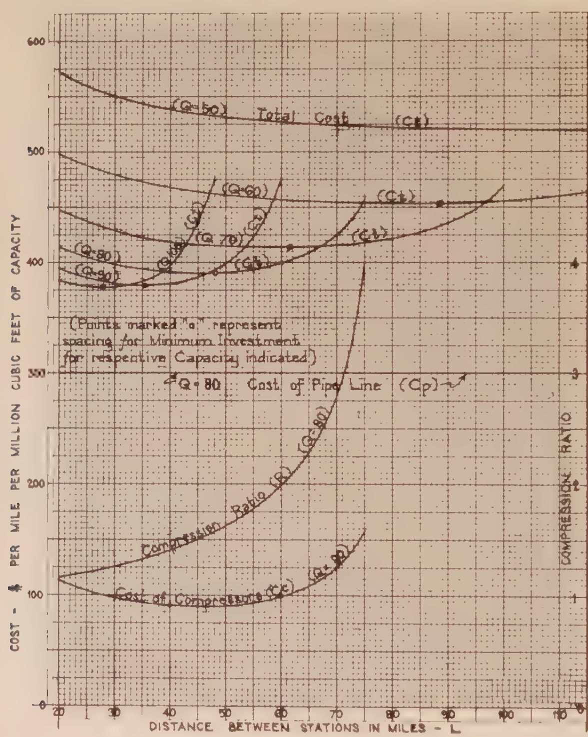

Fig. 6.—Variation of compression ratio with distance between stations.

$D = 18$ in., $P_1 = 414.4$ lb., Q as indicated

chart the variation in the cost per mile per million cu. ft. of capacity, assuming several different required capacities. It develops, as shown, that for small capacities through an assumed line of given diameter, the distance between stations requiring minimum investment should be made large and the compression ratio proportionately high; whereas, if the required delivery is increased, the distance between stations must be decreased and the compression ratio may be proportionately lowered, all to effect the most economical combination of spacing and compression ratio.

Effect of Operating Expenses

All of the foregoing analysis has been upon the basis of the investment required in plant. There is also to be considered, of course, the effect upon design of the expenses of operating the property.

The cost of maintaining the pipe line itself is minor, providing a good construction job is obtained at the outset, and this operating cost is prac-

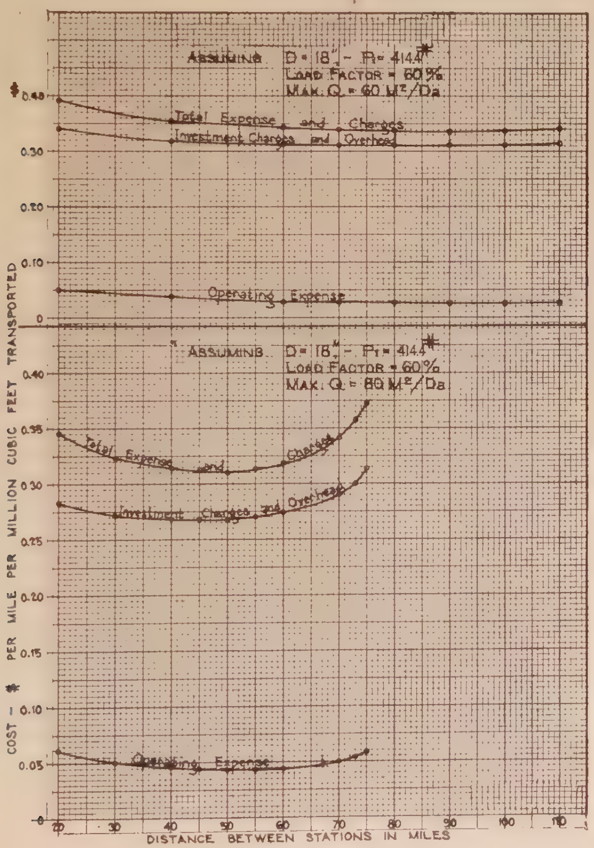

Fig. 7.—Variation of costs.

tically proportional to the value or weight of the pipe, so that its effect upon the design is very similar to that of the investment required. The cost of operating the compressor plants, however, varies somewhat directly with the number of plants or inversely with the distance between plants. From this standpoint the greater the distance between stations the less the operating expense per million transported. However, the compressor plant operation cost also varies to some extent in proportion to the horsepower installed in each station and in the system as a whole;

and this consideration has the effect of indicating a minimum operating expense where the stations are spaced so that the total horsepower is a minimum. In general, from an operating standpoint it is a little more economical to space compressing stations slightly farther apart than indicated by analysis of the most economical spacing for investment purposes. The cost per million transported, on account of interest, amortization, and investment overhead, is ordinarily relatively larger than the straight operating expenses, and the effect of the former should be given more weight. On Fig. 7 the two are put together and the resultant obtained, to show the relation between them as well as the variation in all costs for different assumed station spacing.

Example

A natural gas transmission line 210 miles long recently designed was built of 18-in. OD lapweld steel pipe $^5/_{16}$ and $^{11}/_{32}$ in. thick. The

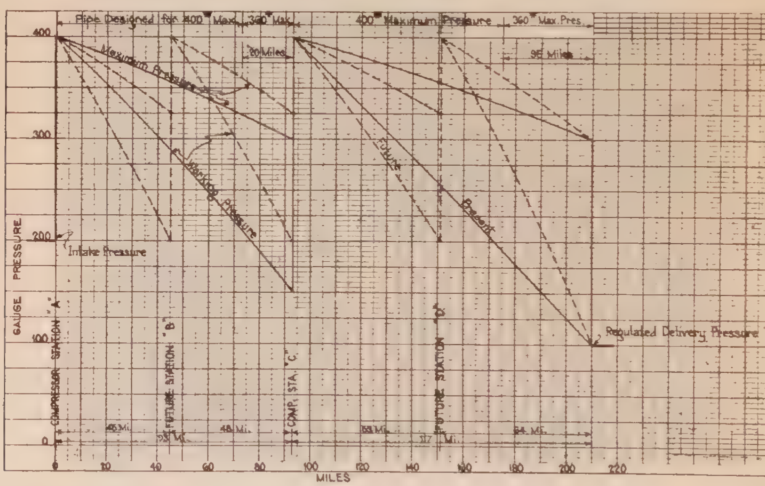

FIG. 8.- PRESSURE DIAGRAM; 18-IN. NATURAL GAS LINE FROM MONROE FIELD, LOUISIANA, TO MEMPHIS, TENN.

heavier of the two weights employed was used at the discharge of compressor stations; and the lighter pipe at the suction end of the present station midway along the line, and for 35 miles leading into the discharge terminal. Two compressor stations were built, one at the field receiving point and the other 93 miles from the field and 117 miles from the discharge terminal. An intermediate station between these two and another station between the present line station and the discharge terminal are planned to be built when the market increases sufficiently to require them. The compressor station spacing, and the operating and maximum pressure design are illustrated in the accompanying Fig. 8.

Conclusions

The design of any large, high-pressure gas line system naturally falls into the following somewhat separate problems:

1. The choice of the diameter and weight of pipe and maximum working pressure. For most economical design, these should be so selected that (*a*) the thickness of pipe will be not less than a practical, safe minimum, (*b*) the working pressure allowable will be equal to that safely provided by this minimum wall thickness and (*c*) the diameter will be as large, within practical limits, as necessary to produce, in conjunction with the working pressure, the delivery capacity required.

2. The spacing between compressor plants and the necessary corresponding compression ratio should be so determined that the cost of installation and operation of the complete pipe line system, including the compressor plants, will be a minimum.

3. Finally, the selection of pipe in (1) and of compressor installation in (2) should both be made with an eye to the proper relation between investment and operating costs, and so that the combination of all factors will result in a minimum total of investment charges and operating expenses per unit of gas transported.

INDEX

(NOTE: In this index the names of authors of papers and discussions and of men referred to are printed in SMALL CAPITALS, and the titles of papers in *italics*.)

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